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Abstract

This working paper provides a longitudinal perspective on the business history of solar energy between the nineteenth century and the present day. Its covers early attempts to develop solar energy, the use of passive solar in architecture before World War 2, and the subsequent growth of the modern photovoltaic industry. It explores the role of entrepreneurial actors, sometimes motivated by broad social and environmental agendas, whose strategies to build viable business models proved crucially dependent on two exogenous factors: the prices of alternative conventional fuels and public policy. Supportive public policies in various geographies facilitated the commercialization of photovoltaic technologies, but they also encouraged rent-seeking and inefficiencies, while policy shifts resulted in a regular boom and bust cycle. The perceived long-term potential of solar energy, combined with the capital-intensity and cyclical nature of the industry, led to large electronics, oil and engineering companies buying entrepreneurial firms in successive generations. These firms became important drivers of innovation and scale, but they also found solar to be an industry in which achieving a viable business model proved a chimera, whilst waves of creative destruction became the norm.

"Power from Sunshine"[1]: A Business History of Solar Energy*

Introduction

This working paper reviews the business history of solar energy from the nineteenth century to the present. It forms part of a wider project to reconstruct the history of "green" entrepreneurship. A companion paper published has reviewed the business history of wind energy. It tracked the idiosyncratic global distribution of wind energy capacity over time, and debated the relative importance of visionary entrepreneurs and public policy in shaping the corporate structure of the industry.[2]

The history of solar contains similarities to wind energy, but also considerable differences. Like wind, the sun is an obvious source of energy, which has long attracted interest, primarily as a source of heat. Like wind also, but even more dramatically, solar energy has never lived up to the potential which its adherents claimed. Even today, as Appendix Table 1 shows, Germany and Spain are the only countries where solar energy accounts for more than 1 per cent of the electricity generated. Although the sun shined everywhere on the planet, the spatial distribution of solar energy capacity has been highly skewed, and not well correlated with resource endowment. Cloudy Germany has more photovoltaic capacity installed than the rest of the world combined. (Appendix Table 2) Manufacture of photovoltaic (PV) cells has also been highly skewed. After being primarily concentrated in the United States for decades, two-thirds of production is now in Asia. (Appendix Tables 3 and 4)

Unlike wind, however, the technology of solar energy experienced a fundamental re-invention following the development of the photovoltaic cell (PV) after World War 2. This resulted in the creation of a far more capital and science-intensive industry than wind energy. The contemporary PV solar industry came to consist of three separate sectors.[3] The first is wafer, cell and module production, the primary focus of this working paper. The second is the installation of such solar cells. The third is the manufacture of polysilicon, the primary raw material used to manufacture PV cells. Polysilicon was the vital component for the new electronics industry which emerged after the invention of the transitor, because it was a semiconductor whose electrical characteristics could be precisely adjusted. Until the turn of the century the solar industry sourced supplies of polysilicon from the byproducts produced for electronic use.

The development of solar energy on a commercial basis turned out to be a lengthy process whose progress was primarily shaped by the price and cost of alternative conventional energy sources. Solar was especially vulnerable to the price of competitor sources of energy as it emerged as the most expensive renewable energy. Innovation was driven by visionary entrepreneurs, all of whom faced the problem that PV solar was a highly capital-intensive and technologically-complex product. This led them to seek investments from large established firms in cognate industries, especially electronics and petroleum, and to rely on public policy to facilitate the growth of the industry. This reliance on large firms and governments was to turn out to be problematic.

Solar before Photovoltaic Cells

The idea of using the power of the sun for heating and lighting was intuitive. Passive solar energy has been used as a form of light and heat since early mankind. In the 5th century B.C., the ancient Greeks designed their homes to capture the sun's heat during the winter. Later, the Romans improved on solar architecture by covering south-facing windows with clear materials such as mica or glass, preventing the escape of solar heat captured during the day. In the 1760s, the Swiss scientist Horace de Saussure built an insulated rectangular box with a glass cover that became the prototype for solar collectors used to heat water.[4]

During 19th century, inventors and entrepreneurs in Europe and the U.S. developed solar energy technologies that would form the basis of modern designs. In 1839, nineteen-year-old Edmund Becquerel, a French experimental physicist, discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes. Becquerel found that certain materials would produce small amounts of electric current when exposed to light.[5] Later, in 1878, a solar-powered steam engine was invented by a French mathematician, August Mouchet, after receiving funding from the French government to work on an alternative source of energy. He created the first solar steam-powered plant using parabolic dish collectors. The plant was a central attraction of the World Exposition in Paris in 1878. This method of creating solar energy is still used today, although the French government didn't provide further funding as it was deemed too expensive.[6] There was enormous interest in the potential of solar energy over the following decades. Between 1880 and 1914 one estimate is that there were almost fifty articles on solar energy published in *Scientific American*, the influential popular science magazine.[7]

It was another matter to develop the commercial use the use of solar energy at a time when fossil fuels were cheap and widely available, and the downsides of their use not understood. The first entrepreneurial endeavors in solar, then, took place in particular locations where using the sun rather than coal made greater sense. During the 1890s several solar water heater companies were started in California, which had a lot of sun and no coal. The first hot water heaters were simply bare metal tanks turned towards the sun. In 1891 Clarence Kemp invented his Climax solar water heater, which put his water tanks inside a pine box fronted with glass, and trapped the heat from the sun. By 1900 1,600 of these heaters had been sold in southern California.[8] In 1908 William J. Bailey, a former mechanical engineer at the Carnegie Steel Company who had moved to California for health reasons, invented a solar thermal collector. He separated the solar water heater into two parts: a heating element exposed to the sun and an insulated storage unit tucked away in the house so families could have sun heated water day and night and early the next morning. The heating element consisted of pipes attached to a black-painted metal sheet placed in a glass-covered box. Because the water to be heated passed through narrow pipes rather than sat in a large tank, Bailey reduced the volume of water exposed to the sun and therefore the water heated up faster. Providing hotter water for longer periods put Bailey's solar hot water heater, called the Day and Night, at a great advantage over the competition. From 1909, when Bailey started up his business, in 1918, his company had sold more than 4,000 Day and Night Solar Hot Water Heaters.[9]

Another early solar entrepreneur was Aubrey Eneas, who had emigrated from Britain to Boston. After settling in Boston, Eneas drew inspiration from another immigrant John Ericsson, the Swiss-born engineer whose design for the ironclad steam-powered battleship *The Monitor* was widely publicized during the American Civil War. Eneas founded the Solar Motor Company of Boston in 1892. He perceived an opportunity in the arid deserts of the American southwest, where a growing need for steam-powered irrigation and lack of easily accessible (and therefore cheap) coal presented a great opportunity for solar power. After unsuccessful experiments, Eneas adopted Mouchot’s conical reflector design to heat the boiler more evenly and efficiently, producing a greater volume of steam. In 1903 Eneas relocated the Solar Motor Company from Boston to Los Angeles and began aggressively marketing his machine throughout the region.[10] He developed large solar collectors to power steam engines and pumps for agricultural irrigation water, and started selling all around California and Arizona. Unfortunately, the construction methods of these large cone collectors did not resist the strong and unpredictable local weather with hail and strong winds. Eneas eventually withdrew from solar energy believing the costs were too high to make a profit.[11]

Eneas was not alone in leaving solar business. During the 1920's Bailey, responding to the growing supply of cheap natural gas in California, switched to making gas-powered hot water heaters. However his technology was taken up in Florida, where gas was not as cheap as Florida. A real-estate boom during the early 1920s open up a market for solar water heating technologies. The Florida patent rights to the Day and Night technology were purchased by the owner of a building company, Bud Carruthers, who later launched the Solar Water Heater Company in Miami. Within a few years the majority of houses in Miami were equipped with the technology. The company expanded so fast that it occupied an entire block of the city within two years. However the success was short-lived, in 1926 the company failed following a massive hurricane and the end of the Florida's building boom. There was a second solar boom in Florida after 1935, when Federal Housing Administration mortgage programs facilitated a housing book in which solar heaters were widely installed. However rising copper prices after the outbreak of the Pacific War ended this boom.[12]

It was in the developing, rather than the developed world, where more ambitious schemes were launched. The first attempt at harvesting energy from the sun in a developing country was initiated by William Adams in the 1870s; an engineer who served as deputy registrar of the High Court at Bombay. Before leaving Britain for his post in India, Adams served in the British patent office in London, a position that triggered his interest in energy technology and its recent developments. Adams accumulated through these years a tremendous amount of information on energy technologies, including solar energy. He was particularly interested by Mouchot's research. In the introduction to a book he published in Bombay in 1878 called *Solar Heat: A Substitute Fuel in Tropical Countries,* Adams wrote about Mouchot's discoveries:

"This idea may be, and probably is, purely Utopian, but very important discoveries have been made in striving for the impossible; and if no further success is achieved than that of utilizing the rays of the sun for driving stationary steam engines, an important addition to physical science will have been made, and a great commercial revolution will have been effected."[13]

Adams came up with a plan to use concentrated sunlight to make the kind of high-pressure steam needed to run modern steam engines. When the first boilers imported from Britain were installed and running, Adams spent a few months perfecting his technology to increase the steam production capacity of his boilers. However the colonial government was extremely skeptical that solar heat could be scaled up for use in commercial, large-scale purposes. The government engineers noted that the limited power storage capacity of Adam's machines meant that workers had to arrive well before dawn to get the boilers started, and had to be sent back home when the sun wasn't strong enough. In response to this criticism, Adams argued – unsuccessfully - that solar energy could supplement coal, which was imported from Britain and costly.[14]

Adams frustration prompted him to abandon further experiments and focus on writing his book. His research, however, sparked the interest of officials in other British colonies with hot climates and no fossil fuels. Aden, for example, faced both these issues, and in addition faced a scarcity of potable water, which had to be distilled from seawater, and sold at an expensive price. Local engineers adapted Adams' apparatus successfully and used it to produce drinking water until cheap oil from the Arabian peninsula replaced coal after the WWII.[15]

The greatest progress in the use of solar power was in the British protectorate of Egypt, where the American entrepreneur Frank Shuman established a solar business. Shuman was a Philadelphia inventor who had become rich through inventing a shatter-proof glass used for skylights, car windshields, goggles and machine tool guards. Shuman began experimenting with solar motors in 1906. Well aware of Eneas's failures a few years earlier, Shuman worked on a simpler, sturdier, less-expensive design for a solar engine. After a year of lab experiments, in the summer of 1907 Shuman built a small-scale demonstration plant in his backyard. To promote his solar motor and trigger interest among potential investors, Shuman circulated advertisements throughout the city inviting the public to attend a demonstration of the sun machine. By 1910, in order to test his design Shuman built on his compound, a plant roughly 10 times the size of the original installation, the total sun collection area was more than 10,000 square feet. It produced around 600 pounds of steam per hour, and generated 25 horsepower—enough to pump 3000 gallons of water per minute to a height of 33 feet.[16]

Shuman was convinced he could make a breakthrough in commercial solar power. In order to compete with coal, Shuman thought, a solar plants would need to be much larger. He was soon envisaging 10,000 horsepower steam engines run by sun collectors covering 60 acres.[17] In September 1911 he wrote in *Scientific American*:

"The future development of solar power has no limit. Where great natural water powers exist, sun power cannot compete; but sun-power generators will, in the near future, displace all other forms of mechanical power over at least 10 per cent of the earth's land surface; and in the far distant future, natural fuels having been exhausted it will remain as the only means of existence of the human race."[18]

Building on alarmist newspaper headlines predicted an imminent energy crisis due to shortages of coal and petroleum, he described an exciting solar future where “deserts in remote corners of the world could be made to bloom with the aid of sun-powered irrigation”. Shuman confidently predicted, solar energy would be a main source of power across the globe within decades.[19]

After failing to attract investor interest in the United States, Shuman turned to London, the world’s biggest and most global equity market, where his where his colleague and consultant, British engineer A.S.E. Ackermann, had contacts in scientific and investment circles. The considerable number of British possessions in tropical countries had already stimulated a search for alternatives to imported coal or oil. In 1911 Shuman and his partners floated a new company, Sun Power Company (Eastern Hemisphere) and persuaded a sufficient number of investors to buy its shares to launch a solar energy venture in Egypt.[20]

Shuman was attracted to Egypt both as it had a lot of sun, and because mechanized irrigation was ever increasing as the lands adjacent to the Nile River were arable only with proper irrigation. Shuman leased land in the farming village of Meadi—which was also the administrative center of Egypt —and prepared to have parts for an experimental plant shipped from Philadelphia to Egypt. Shuman project was soon interrupted by the government’s engineering consultant to the government who sought costly improvements.[21] To save on costs Shuman decided to build the plant from scratch in Meadi, using local materials instead of building parts in Philadelphia and having them shipped to Egypt. The first commercial scale solar plant was successfully launched. The British administration, thrilled at having found a cost-effective way to upgrade Egypt’s irrigation system and increase the country’s lucrative cotton crop, offered Shuman a 30,000- acre cotton plantation in British Sudan on which to build a larger version of the solar plant. Because of the rivalry between Germany, England and France over the Middle East and Africa, the German government took notice of the potential of solar in colonies and awarded Shuman $200,000 to design and construct a solar-powered irrigation system in East Africa. This success led the inventor to envision even larger solar power plants, including a project of a 20,000 square mile plant in the Sahara desert to generate 270 million horsepower—an amount, he noted, equal to all the fuel burned around the world in 1909.[22]

Shuman's ambitious solar plans were brought to an end by the outbreak of World War 1. Engineers working at the Meadi plant, including Shuman, returned to their home countries and within several months the plant itself was dismantled for parts and scrap metal. Shuman died of a heart attack in 1918.[23] After the end of the War, the momentum for further experimentation was lost, as the prices of fossil fuels fell sharply during the postwar recession, and then fell again after the outbreak of the Great Depression in 1929.[24]

Solar Homes

The first engineered passive solar houses of the modern era were built in Germany after World War I, when the Allies occupied the Ruhr area, including most of Germany's coal mines.[25] From the 1930s the American architect George F. Keck experimented with the basic principles of passive solar houses.[26] He designed the all-glass "House of Tomorrow" for the 1933 Century of Progress Exposition in Chicago,[27] and noted that it was warm inside on sunny winter days prior to the installation of the furnace. Following this, he gradually started incorporating more south-facing windows into his designs for his clients. In 1940 he designed a passive solar home for real estate developer Howard Sloan in Glenview, Illinois. Named the "solar house" by the Chicago Tribune, the Sloan House became first house to carry this name. Sloan continued to build numerous passive solar houses, which contributed to the emergence of a "solar house" movement in the 1940s.[28]

During the 1930s researchers at the Massachusetts Institute of Technology (MIT) also experimented with solar home designs that incorporated pumps and storage devices. MIT's Solar 1 house was completed in 1939 to demonstrate how the sun could heat houses in the winter, and MIT researchers also conducted experiments to judge the possibility of solar-powered air conditioning and energy generation. In 1938, Godfrey Lowell Cabot, the Boston industrialist and pioneer aviator, gave a gift to MIT to be used specifically for "the art of converting the energy of the sun to the use of man." [29]

In the United States interest in energy efficiency emerged during the Second World War when potential energy shortages became an issue. In addition, technology advances in the glass industry allowed homebuilders in cold climates to use larger window area. In 1945, the Libbey-Owens-Ford Glass Company, which in the previous decade had been experimenting with double-glazing windows in order to retain heat, initiated a large scale solar house project after receiving numerous letters from prospective home buyers interested in energy efficient houses. The company planned to build solar houses in 48 states and selected local architects to design these houses, using a jury composed of editors, university deans and other key personalities in the building industry.[30] The project was launched but encountered harsh criticism. Purdue University engineering professor F.W Hutchison, conducted extensive experiments on these constructions and concluded that passive solar houses "may be net money losers in terms of heating costs"[31], in the end, the solar house movement failed to create a community of solar architects or to launch a widespread solar house movement after 1947. Instead, with the boost of "all electric houses" architects gained increasing interest in the late 1940s on the possibilities of electric cooling and heating.[32]

Passive solar was also employed by a new generation of modernist architects who became influential in mid-twentieth century America. Carl Koch was a Cambridge, MA-based architect who was educated at Harvard and had studied under Walter Gropius, the Bauhaus founder. Koch traveled to Sweden on a fellowship in 1938, and was struck how Swedes had begun to prefabricate. He began working on building houses that were significantly cheaper, but still fully functional and pleasant homes. Koch's first project, in 1941, upon returning to the United States was a community housing project called Snake Hill in Belmont, Massachusetts. Koch developed the project as a way to design an inexpensive home for himself and his family, who moved into the one of the complex's five original houses built on a rocky hillside, which had previously been regarded as uninhabitable.

This experience inspired Koch to pursue a career in creating quality affordable housing for American families. He believed that the best post-World War-II housing solution for the shifting and expanding American population was the creation of demountable, prefabricated housing. Koch developed the “Techbuilt House” in 1954, designed with prefabricated components that could be custom assembled to create houses that were unique to the needs of the client, but could benefit from the affordability of mass production. Koch designed houses with post-and-beam construction that allowed for the large expanses of glazing. The exterior design was characterized by a single gable roof, large plate glass windows on the gable ends, and deep eaves. Techbuilt houses often were designed around a common family “hearth,” featured built-in prefabricated furniture systems, and celebrated the connection to the outside through large expanses of windows and outdoor rooms. Although Koch is not celebrated as a solar pioneer, the large windows made effective use of passive solar heat. Koch was concerned, broadly, with sustainability issues. In his book about his architectural work written in 1958, Koch wrote of his hopes that in the future “atomic or solar energy” would provide the cheap electricity needed for heating and cooling.[33]

Architects continued to experiment with passive solar during the postwar decades. During the 1950s Felix Trombe in France built houses where the entire south wall consisted of thick masonry with few or no windows. The wall was faced with glass or other material which allowed sunlight to pass through to the masonry but inhibited re-radiation of the heat outward. As a result the south wall accumulated heat during the day and gave it up gradually to the interior of the house at night. The substantial downside was the loss of any view. During the 1970s, as energy prices soared, solar hot-water systems made a re-appearance in the United States, with small companies selling systems which employed flat-plate collectors on south-facing roofs.[34]

The Photovoltaic Cell and the New Solar Industry in the United States

The solar industry was re-invented through the development of the photovoltaic cell (hereafter PV). PV cells converted solar radiation directly into electricity. When photons of sunlight strike the cell, electrons are knocked free from silicon atoms and are drawn off by a grid of metal conductors, yielding a flow of direct current. It was, at least potentially, a dream technology. An article in *Science* magazine noted:

“If there is a dream solar technology it is probably photovoltaics – solar cells…They have no moving parts and are consequently quiet, extremely reliable, and easy to operate. Photovoltaic cells are a space age electronic marvel, at once the most sophisticated solar technology and the simplest, most environmentally benign source of electricity yet conceived.”[35]

The new technology had its origins in the postwar United States. The story began at Bell Laboratories, the research facility of AT&T which was famously responsible for inventing television, lasers and transistors, and much else.[36] Russell Ohl's invention of the silicon solar battery in 1946 was a key breakthrough. Ohl, who had joined Bell Laboratories in 1927, was a physicist whose specialized area of research was the behavior of crystals. In 1939 Ohl discovered the PN barrier "P–N junction". There was little known about the impurities within crystals, but Ohl discovered the mechanism by which it worked. It was the impurities which made some sections more resistant to electrical flow than others, and thus it was the "barrier" between these areas of different purity that made the crystal work. Ohl later found that super-purifying germanium was the key to making repeatable and usable semiconductor material for diodes. His work with diodes led him later to develop the first silicon solar cell, and in 1946 he filed a US patent for a "Light sensitive device". [37]

In 1954 other Bell Laboratory scientists invented the first PV cell which could produce significant electric power. Daryl Chaplin had joined Bell labs in 1930, and in the early 1950s began working on finding new sources of power for transistor telephones. This led to experiments with converting solar energy into electrical energy. Chaplin, and fellow scientists Gerald Pearson and Calvin Fuller, used strips of silicon placed in sunlight to capture free electrons and turn them into sunlight. Their public demonstration of the cell inspired a 1954 *New York Times* article to predict that solar cells would eventually lead "to the realization of one of mankind's most cherished dreams -- the harnessing of the almost limitless energy of the sun."[38]The silicon photovoltaic invention by Bell Labs came to the attention of the recently created US space program. PV solar cells appeared as potential solution to power those satellites. [39]

The Bell PV solar cell coincided with a renewal of interest in solar energy more generally. In 1953 a multi-volume report to the U.S. President by W.S. Paley on "Resources for Freedom" had made the case that fossil fuels seemed to be in declining supply. This stimulated the formation of an Association for Applied Solar Energy in 1954. In November of the following year it organized two conferences, one on the scientific basis of solar energy in Tuscon, followed by a World Symposium on Applied Solar Energy in Phoenix. These meetings attracted delegates from 37 countries, and Bell's PV cell was exhibited. The Association energetically pursued new prospects for solar energy. In 1957 it held an International Architectural Solar House Competition which attracted more than 1,000 architects from 36 countries. The winning design was never built.[40]

The commercialization of the production of PV cells turned out to be very complex, and was led by small entrepreneurial firms. A pioneer was Hoffman Electronics, founded in Los Angeles by Leslie Hoffman in 1946. He started manufacturing small tube radios, and in 1948 moved into televisions. During the 1950s the firm began manufacturing semiconductors. In 1956, the company acquired National Fabricated Products, which owned the original patent license of the PV Bell Labs technology. Hoffman's solar cells were used in satellites, beginning with the first Vanguard I, in 1958. This satellite used a small, less than one watt, solar array to power its radios. Hoffman worked steadily to increase the efficiency of solar cells. In 1958 it created an 8% efficient solar cell. Within two years it had a 14% efficient solar cell.[41]

A second entrepreneurial venture in solar cells was created by Alfred Mann. After growing up poor in Portland, Oregon, and selling lemonade and magazines during the Great Depression, he studied physics at UCLA during the late 1940s. His interest in studying light led to a first job with Technicolor, a Los Angeles firm whose color film processes dominated the Hollywood film industry. The Army approached Technicolor for help with light filtering for a missile guidance system but, when Technicolor did not want the work, Mann pursued the $11,200 Army contract by leaving the company and forming a small company called Spectrolab in 1956. Two years later Mann was approached by someone from the Air Force who said they wanted to build a spacecraft powered with solar cells, but there was a problem that solar cells lost efficiency when they got hot. As Mann later recalled,

"I thought about it and decided that maybe we could apply a coating to the solar cells that would make them run cooler and be more efficient in space. They gave me a purchase order to make some samples. The samples worked well and they gave us a contract for the first spacecraft. They liked our workmanship and our competence. Later they wanted us to assemble the solar panels. We really didn't want to do that, but the company that was assembling them was not doing well, so we thought about it long and hard. ... We got the contract and as it turns out we were very profitable." [42]

Mann placed the production of solar cells in another company he had founded, Heliotech, which made semiconductors. In 1960 Mann sold Spectrolab and Heliotech subsidiaries to the fast-growing conglomerate Textron, which was building a presence in military procurement. In the same year it acquired Bell Aircraft, which had helped design the first aircraft to surpass the speed of sound. Bell also built many of the X-1's successors. Hoffmann Electronics continued in the solar cell business, and within a year was suing Textron for hiring away its engineers to learn trade secrets.[43]

The prospect of government contracts encouraged other large electronics companies to experiment with the solar market. These included the radio and television manufacturer RCA, and the semiconductor companies such as Texas Instruments. Universities and research institutes invested in solar, on a modest scale. The solar market in the United States, however, remained small. The primary market was powering satellites, so NASA provided the major market. In 1964 NASA launched the first Nimbus satellite powered by a 470-watt PV array. During the 1960s and 1970s the annual market of solar cells was worth about $5 to $10 million for a 50 to 100 KW of capacity.[44] (See Appendix Table 2)

This market was tiny in the context of the overall energy market. The low and often falling costs of fossil fuels meant that it rarely made financial sense to invest in solar technology, except for a specialized purpose such as space exploration. Moreover, during the postwar decades nuclear fission was wildly seen as offering the potential of unlimited and cheap energy. This was, as one contemporary wrote, "a dominant factor in casting a vote against the need for looking at any other energy options."[45] There was a further issue also. Although solar industry was classified as "renewable", the manufacture of PV cells was not without adverse consequences for the environment. PV manufacture used many of the same chemicals as heavy metals used in semiconductor manufacture. In particular, there was the issue of the length of time which cells needed to operate to produce as much energy as was used to manufacture them.[46]

Solar and the Oil Crisis of the 1970s

The oil price rises of 1973-4 and 1978-9 ended for the moment the era of cheap oil which had characterized the postwar decades, while raising major concerns about the security of oil supplies. This encouraged governments everywhere to reconsider energy supplies and consumption, but with policy variations between countries. France and Sweden, for example, launched a major nuclear energy program.[47]

In some countries, alternative energy sources like wind and solar were looked at with new interest, especially because of growing environment concerns. In 1972 the United Nations held its first Conference on the Human Environment in Stockholm. This launched an Environment Program. Although little concrete emerged from this, the potential of solar energy became more widely discussed than previously. One report in 1977, for example, lauded the potential of solar energy for the Mediterranean region. This energy resource, the report observed, was renewable, "clean" and well-distributed. "Solar energy", it continued, "is the only possible solution for countries which are poor in fossil energy but which do not wish to be totally dependent either on oil or on the atom for their supplies."[48]

The United States had both oil and nuclear energy, but the oil crises also raised new interest in alternative energy. Peter Glaser, a Vice President of Arthur D. Little, the Cambridge, Massachusetts firm of management consultants, was an enthusiast for solar energy even before the oil crises.[49] After 1973 the firm was engaged in multiple projects related to solar energy. It had contracts from NASA to explore solar power applications to satellites. In that year launched a project under a contract from the Electric Power Research Institute to explore the prospects of developing a "solar climate control industry", which would involve developing solar-powered systems for heat storage, air conditioning and other equipment. The project was pursued with considerable investment through to 1980.[50] Glaser also used the firm's knowledge of satellite technology to pursue a project on how solar energy in space could be captured and employed to generate electricity on earth.[51]

In 1974 the Ford Foundation produced a major report entitled "A Time to Choose: America's Energy Future." The report took a nuanced short and long-term view of energy supplies from all sources, including the prospects for making fossil fuels such as coal much cleaner than at present. A striking feature of the report was its clear identification of issues which would continue to be discussed for the next four decades. The report talked in detail about the greenhouse effect, and the several indications that man's use of fossil fuels is altering the global climate." The report dealt in detail with the importance and potential of nuclear energy in solving long-term energy needs, before drawing attention to both "the risks of nuclear power" and the lack of sustainable solutions to waste storage.[52] Solar energy did not feature prominently in the report, but it did feature as the "world's most abundant renewable energy resource." The authors were especially impressed with the prospects for solar heating and cooling in buildings, and asserted that the technologies for more fundamental use of solar in the generation of electricity were on the threshold of taking off – if the government would provide as much seed money as it had earlier for nuclear energy.[53]

This level of support for solar, however, was not forthcoming. However, the Federal government did re-organize its energy bureaucracy, creating the Energy Research and Development Administration. Nuclear and coal were still seen as the main sources of electricity, though wind and solar now received some attention.[54] The most significant government initiative was the Solar Energy Research Development and Demonstration Act of 1974. Originally called the Solar Energy Research Institute, the National Renewable Energy Laboratory (NREL) began operating in Golden, Colorado in July 1977. However funding for solar remained modest. The greater problem was, as in the case of wind energy, a government mindset focused on defense and space contracting, which led to a preference for big and expensive projects.[55] During Congressional hearings in 1978, Jim Harding of Friends of the Earth, and the co-author of a large study about the benefits of solar energy, unfavorably compared US spending with the advances in solar-heated home technology seen in Germany, Denmark and Canada. Harding noted the program was “ill-funded”, but also that “much of the money has been misused…our U.S. solar program is an international embarrassment. It is an embarrassment because it stresses overbuilt, over –designed, far too expensive technologies that will never be solutions.”[56]

These Congressional hearings were noteworthy for their identification of the problems which would beset US government policy for decades. A representative of the Worldwatch Institute told the Committee that “there is no substitute for money. While competing energy sources have financially benefitted from the diligent efforts of scores of highly-paid lobbyists, solar energy has not”.[57] A consulting engineer on the faculty of the School of Architecture at the University of Southern California, noted that the growth of the US had

“been based on cheap energy..we have done everything we can to make it easy to build cheaply, and inefficiently and then to subsidize it by operating with cheap energy…These same policies prevent us from going into more energy efficient scenarios, as for example, solar technology. We are always asked, why don’t we go solar, and then, what kind of a payoff is there.”[58]

In the same year a set of public policies aimed at stimulating demand for alternative energy proved important for both the solar and wind energy businesses in the United States. The Public Utility Regulatory Policies Act (PURPA) of 1978 opened the door to competition in the electricity supply by requiring utility companies to buy electricity from “qualifying facilities” also known as “nonutility facilities that produce electric power” including renewable power plants. The 1978 Energy Tax Act also offered a 30-percent investment tax credit for residential consumers for solar and wind energy equipment and a 10-percent investment tax credit for business consumers for the installation of solar, wind, and geothermal, technologies. The utility commissioners of individual states were left to implement the rules.[59]

The state of California under Governor Jerry Brown took the most radical measures to promote alternative energy. In 1978 Brown established a SolarCal office to co-ordinate solar energy programs within the state with the state architect, Sim van der Ryn, who was in charge of a $200 million solar and conservationist program. Van der Ryn was particularly concerned to build energy efficient public buildings, and installed solar energy in them. As he remembered much later,

"At that time we needed more office space, because Reagan has taken all the space in the suburbs for his friends, you know… republican contractors and real-estate speculators. At that time the state wasn't broke, and we figured, it would be cheaper on the long run to build our own buildings (public offices) instead of leasing them. Those buildings needed to be energy efficient…I remember going to the legislature and walking in with a one gallon gas tank and I told them, 'it takes a gallon of oil to heat and cool a square foot of this state office by the time I'm done here, I'll reduce it to a tea cup.' They thought it was a little crazy, but the graphic example intrigued them, and literally we were able to do that."[60]

The Californian state, more generally, also offered a 55 per cent credit against State income tax credit for people who bought solar energy systems. This credit was given both to consumers and to house builders in order to encourage the use of multiple solar designs in houses. The program was designed to expand the market sufficiently to capture scale economies and eventually lower prices."[61]

Federal support for solar rose to a new height under the administration of President Carter. Carter had entered office concerned about energy consumption and supply – in April 1977 he had labeled the energy problem "the moral equivalent of war," but had not been especially concerned about alternative energy sources. However the Iranian Revolution and the second oil shock in 1979 resulted in a swathe of measures designed to stimulate domestic production, develop synthetic fossil fuels, constrain oil consumption, and develop wind and solar power.[62] In 1979 the administration announced a new $3 billion program of research into solar industry, which included installing a showcase solar heater at the White House.[63] By the early 1980s the US represented 80 per cent of the world market for solar energy. US-based companies accounted for 85 per cent of world sales.[64] The United States exported 45 per cent of its production and dominated world markets.[65]

Searching for Scale

The rise of Federal and state government investment in solar energy prompted the entry of new entrepreneurial actors in the United States interested in transitioning the industry from the space program to new markets on earth. This turned out to be an expensive proposition, both in terms of capital and in terms of the time taken to develop technologies. Much earlier than in wind energy, entrepreneurs in solar found themselves turning to big corporations. The results were mixed.

In the United States, oil companies emerged as key investors. There were multiple motivations, but initially one stood out: solar was a potential solution to a specific operational problem of powering offshore platforms. By 1980, solar powered navigation systems were installed in all production platforms in the Gulf of Mexico. At that date, oil companies accounted for 70 per cent of all the solar modules sold in the United States.[66] Table 1 lists the major US oil company investments in solar during these decades.

Table 1 Major U.S. Oil Company Investments in Solar Energy 1970-1980

Date	**Firm**	Strategy	**Outcome**
1973	Exxon	Creates Solar Power	Sold to Solarex in 1984
1974	Mobil	Joint Venture with Tyco	Sold to ASE 1994
1977	Arco	Acquires Solar Power	Sold to Siemens 1990
1979	Amoco	Invests in Solarex (100% in1983)	Amoco acquired by BP 1999

These large investments from oil companies began with the activities of Elliot Berman, a New Jersey-based industrial chemist. In 1972 Berman developed a new, cheaper type of solar cell based on organic materials such as dyes. During the 1960s Berman had worked for the Itek Corporation, a US defense contractor which made cameras for spy satellites. Itek was, like many companies at the time, concerned to diversify its business, and Berman successfully facilitated their entry into the photographic materials business. In 1968 the firm invited Berman to consider new businesses, and he determined that he wanted to develop products which had a major social impact. He identified a correlation between "energy availability and quality of life," and began to consider ways to provide electrical power for the rural poor in developing countries. He found the solution in the promise of solar energy. In view of the high cost of silicon cells, he suggested that the company needed to invest in a new type of solar cell, made from the photographic film on which he had worked. Itek did not proceed with the project.[67]

Berman left his company, and spent six months attempting to interest venture capitalists and others in his proposed solar project. After eighteenth months a chance conversation led Berman to Exxon, which had just begun to consider looking at alternative energies in the expectation that conventional energy prices would raise substantially over the following decades. Berman moved his lab into the oil company, and started developing this new technology. The organic cells he was proposing would take years to develop, in the meantime, he decided to buy conventional silicon solar cells with which he commercialized an interim product.[68] Berman first tried to purchase these cells from a small company named Centralab, but all the company had to sell were rejects from the space program which was far from enough to meet his needs. He then decided to fly to Japan, to meet with the Japanese company Sharp, which had been producing solar cells for over a decade. Berman and Sharp could not agree on a price, and no agreement was reached.[69]

Berman realized he needed to manufacture these silicon solar cells himself. In April 1973, he launched Solar Power Corporation, a fully owned subsidiary of Exxon. This was the first company established to specifically manufacture terrestrial PV cells in the U.S. Berman did not use the expensive pure semiconductor-grade crystalline silicon employed in the space industry, but instead cheaper silicon wafers rejected by the semiconductor industry. First introduced to supply power to remote locations (telecommunications, coast guard etc), it was intended in the long run compete with conventional power sources.[70]

Berman initially believed that the US Coast Guard would be the initial primary customer. However the Coast Guard, noting the diversity of geographical conditions it faced, declined to commit.[71] Instead, Berman started manufacturing solar cells to be used on Exxon's off-shore platform in the Gulf of Mexico. According to Berman "We went and visited some Exxon platform in the gulf. What we learned, which everybody down there knew, but nobody at the headquarters knew, is you have one platform that's loaded with power, and that's where all the crews live. However, most of the platforms are unmanned and have no power."[72] At the time, the system for powering platforms relied on large lead-acid batteries, each weighting several hundred pounds and costing over $2,100 each. When exhausted the crew would simply dispose of the batteries in the waters, which had a devastating effect on marine life. In 1978, the Environmental Protection Agency outlawed such disposing of batteries in the ocean, which added a sense of urgency for oil companies to come up with a new way to power their platforms.[73]

A second large US oil company to invest in solar was Mobil. As in the case of Exxon, the origins of their involvement lay in an entrepreneur outside the company. During the 1960s a researcher called Abraham Mlavsky, working with an investment and holding company called Tyco in Waltham, Massachusetts, engaged in semiconductors and energy conversion, developed the process for producing a continuous thin ribbon of silicon that could be separated into suitable lengths, processed into solar cells, and placed in modules. Tyco had developed the technology for growing sapphire tubes for sodium vapor lamps and other products but silicon was a much more difficult material to work with, as temperatures had to be extremely tightly controlled for the silicon to grow continuously. In 1971 NASA, in search of lighter weight solar cells, gave the firm the chance to produce solar cells from ribbon silicon, but were unable to achieve suitable conversion efficiencies. NASA resumed interest two years later, and in 1974 Mobil and Tyco joined forces to begin developing advanced silicon solar cells. Mobil-Tyco spent years attempting to develop efficient production, but by the end of the 1980s they had cut the cost of fabricating crystalline silicon solar cells in half. During the early 1990s a plan was developed to make and sell solar cells to utilities in the desert regions of the western United States to help power residential air-conditioning, but a sharp fall in natural gas prices led to Mobil to divest altogether by selling to the German company ASE.[74]

The entry of Arco, a third US oil company, into solar came through the activities of Joseph Lindmeyer and Peter Varadi. Both were working on space solar cells in the early 1970s for a satellite company called the Communications Satellite Corporation (COMSAT). While at COMSAT, Lindmeyer developed a photovoltaic cell that was 50 per cent more efficient than any other at the time. COMSAT patented and used this technology on all of its space satellites. Lindmeyer did not benefit financially from his invention as he was a salaried employee, and as a consequence he went on to design a new production process that he hoped would cut down the cost of producing photovoltaic cells dramatically, thus making them possible for terrestrial use, but COMSAT was not interested.[75]

In 1973 Lindmeyer and Varadi decided to leave COMSAT to set up their own company to develop terrestrial cells. In February, Solarex was founded. Varadi took on the task of raising funds. In 1972, attempts to obtain funding from venture capitalists were not successful, as they remained wary of photovoltaics and did not trust two scientists to manage a business. But they eventually were able to raise $250,000 from friends and family. Manufacturing began in August. Within eight months, Solarex became profitable. Vardi later recalled,

“Two months after we launched our company the oil crisis happened, in 1973, at that point we got a lot of publicity from the media, and soon enough, instead of us having to find people, people were coming to us from across the country. Also it was very innovative at the time, we were not selling refrigerators so it triggered people’s interest, and people who needed this technology knew where they could get it.”[76]

Solarex’s fast growth was placed in jeopardy when COMSAT sued it for patent infringement in 1974 but the case was promptly dropped. Solarex sales during the first years were concentrated in niche markets, such as powering watches and calculators. Solarex was the first US company to collaborate with Japanese companies to make solar calculators and produced remote-area power supplies for radio repeaters. However these orders were small and not consistent.[77]

Solarex's big breakthrough came in 1979 when it obtained equity funding from two European companies. Holec, a Dutch electrical company, and Leroy-Somer, a French electric power generating company, invested to obtain Solarex's expertise and license in manufacturing photovoltaic cells in order for them to exploit the European markets, but the most significant investment for Solarex was a $7m investment from Amoco. With an apparently booming photovoltaics market due to supportive government policies, Solarex spent $7m on a new "breeder" plant powered by PV cells to produce PV cells. To show its support, Amoco installed Solarex photovoltaic panels on one of the service stations located at its head office in Chicago.[78] In 1978, Lindmeyer described the events of the previous four years to the House Sub-Committee on Solar Energy:

"Terrestrial photovoltaics on any industrial scale is only four years old. We have in this short period changed the outlook on photovoltaic in a dramatic manner, For more than a decade the prices were controlled by the market of the space program which is characteristically small in volume and high in price. Space solar panels are typically around $500/watt, which is so high that terrestrial use is out of the question. Some four years later we are building a system for a community college in Arkansas which will deliver power at some $6/W. We surely feel that tremendous progress was made in the last few years."[79] In 1980 an article in the *New York Times*, on the subject of innovation in America, singled out three companies as exemplars of innovation, Solarex was one of them, alongside Apple and Genentech.[80]

This optimism soon faded. During the early 1980s the combination of a declining oil price and the withdrawal of Federal government support resulted in Solex experiencing difficulties as the solar market stalled. In 1983 Maryland Bank, with which Solarex had a $7m debt, demanded full repayment within three months after becoming alarmed by a reporting mistake by the Solarex CFO. Solarex could not repay the money or refinance. Efforts to find new investors proved fruitless. Amoco acquired full control of Solarex, which joined Solar Power as an oil company-owned venture.

Acquisition by an oil company was also the fate of another entrepreneurial start-up by a former employee of Spectrolab. Bill Yerkes founded Solar Technology International in 1975. Yerkes, a mechanical engineering graduate of Stanford, worked for Chrysler and Boeing, where he built the Boeing Kent Space Environment Laboratory in support of the Apollo lunar landings. After moving to Los Angeles, Yerkes became CEO of Spectrolab, where he was responsible for developing the solar technology which was left behind on the moon by Apollo 11, along with space batteries. During his time at Spectrolab, Yerkes and his wife had opted to live an alternative, environmentally friendly, lifestyle, for nearly two years in a 24-foot house trailer in which all appliances, including an electric composting toilet, were powered solely by PV cells, despite the presence of adjacent power lines.[81]

Yerkes was sacked when Hughes Aircraft acquired Spectrolab in 1975. He was furious, and resolved to build his own solar company. With $80,000 of his own money as seed capital, he founded Solar Technology International in a 4,000-square-foot facility in Chatsworth, New Jersey, and set about trying to reduce the cost of terrestrial solar cells and modules. By getting rid of silicon as the top cover, and replacing it by tempered glass, a more resistant and easily available material, he solved serious maintenance problems. He also restructured cell production method by screen-printing contacts onto the cells. The materials and methods he introduced in the late 1970s became standard for the industry and took costs down.[82]

In 1976, STI got its first significant order from a motor home company which Yerkes convinced to install small panels on its motor homes to keep batteries charged during storage. The Jet Propulsion Laboratory (JPL) - a Federally funded research and development center and NASA field center located in the San Gabriel Valley area of Los Angeles County, California - placed an important order under a US Department of Energy purchase program. STI's panels passed JPL's rigorous testing program, this helped STI to gain the trust of customers and sales picked up subsequently. Yerkes brought in more investors to obtain capital for more advanced manufacturing equipment.[83] Although Yerkes delivered significant innovations, raising further capital proved problematic. In mid-1977, Yerkes sold his company to Atlantic Richfield Oil Company (ARCO), another large US oil company, forming ARCO Solar.[84]

ARCO's investment in solar reflected the firm's longstanding commitment to environment issues. Robert O Anderson, the founder of the firm in the 1940s, was an outspoken proponent of the responsibility of business to solve the world's environmental problems. He was among the supporters of the foundation of Friends of the Earth, and a regular speaker at international events on the need to protect the environment, and was actively involved in the preparations for the United Nations Conference on the Human Environment in Stockholm in 1972. As early as 1969 ARCO itself had appointed a prominent ecologist to work in Alaska as its chief ecologist and environmental advisor, and by the 1970s the firm was highly committed to minimizing environmental pollution from its operations. It responded quickly to the Federal Clean Air Act of 1970 with a low-octane, lead-free gasoline.[85]

During the next decade ARCO invested over $200 million in its new venture, of which Yerkes estimated 90 per cent was defrayed by tax credits.[86] Yerkes remained as vice president of engineering and technology, and scaled up by creating a research laboratory of 100 people in a new 10,000 square feet production facility. However Yerkes quickly encountered the downsides of working with a large oil company. They imported managers who had no understanding of solar technology, and pursued technological options in thin-film silicon which he considered unviable. Going into commercial production in 1980, ARCO built the first production facility of greater than 1 MW capacity. ARCO was involved in several high profile PV projects including utility-scale plants, all in California. In 1982 in built the first privately funded central-station PV plant on the high desert near Hesperia in that state. The plant, which was unmanned, fed electricity into the distribution grid of the Southern California Edison utility.[87] Internationally, ARCO developed partners and sold PVs for off-grid applications into over 80 countries.[88]

ARCO became, for a time, the largest PV manufacturer in the world, and engaged heavily in research, forming a strategy which Anderson described as “growing tomorrow’s new industries.”[89] The firm’s sales reached $40 million in 1988. Yerkes however left the firm in 1985, returning to Boeing. Five years later ARCO sold the solar business, which never generated profits, to Siemens, for an estimated $30-$50 million.[90]

The entry of the oil companies into the solar industry had a number of downsides, especially making it difficult for other entrepreneurial ventures to compete with their now well-funded peers. This was evident in the case of Ishaq Shahryar, another solar visionary. Shahryar had arrived in the United States in 1956 on a scholarship from the government in Afghanistan. He enrolled at the University of California, Santa Barbara, and studied chemistry. On graduation he worked in the semiconductor industry, before joining Spectrolab. With the help of two other scientists, he invented low-cost PV cells and developed the process of screen-printing cells on solar panels, which is still used in the market today. Shahryar had vivid memories of his youth in

Afghanistan, where he had had to study by candle or kerosene light when the electricity supplies went off. He told Yerkes that while the United States might have plentiful electricity, there was a huge potential market in the Middle East and Asia for solar energy. Shahryar had an explicit social agenda- “My goal was rural electrification- a light for students to read by at night”.[91] When Hughes Aircraft bought Spectrolab in 1975 and refocused on space, Shahryar resolved to found his own company, Solec International, Inc**. “**My motivation”, he later wrote, “was what service I could do for other people.” He sold his car, raised $200,000 in investment capital, and secured a $500,000 loan from the Small Business Administration to start a business.[92]

As was a common experience in the solar industry, Solec experienced considerable difficulty building a viable business. It was able to sell to the Jet Propulsion Laboratory, and also benefitted from the Carter stimulus program. In 1981 Shahryar sold 80 per cent of the company to the Pilkington Glass Company in Britain, but after five unprofitable years, the British company sold their holding back to Shahryar. There followed a difficult period, in which the company faced the risk of bankruptcy. In 1987 Solec provided the solar cells for a solar electric race car being built by the hair care entrepreneur and multi-millionaire John Paul DeJoria, an active supporter of environmental issues, who promptly invested $1 million in the struggling venture.[93]

Shahryar’s strategy rested on avoiding direct competition with the oil company financed ventures by focusing on niche markets, such as solar panel systems for lighting bus shelters and streets. He concentrated on improving single-crystal silicons rather than more expensive, thin-film, technologies. By the mid-1990s Shahryar had a modest 2 per cent of the US PV market, and it was profitable, but he still needed funds to build scale.

The Middle East also had a role to play in one of the largest solar businesses of this era. LUZ International was the brainchild of Arnold Goldman, a Rhode Island-born engineering graduate of the University of Southern California. After graduating in 1967, he went to work for the military engineering contractor Litton Industries, and then founded his own company to develop word processing on personal computers. He sold his shares in 1977, becoming wealthy, and moved to Israel to write a book of philosophy and social theory which he started almost two decades earlier. Goldman envisaged the creation of a utopian city, which he named LUZ after the Biblical city where Jacob dreamed of a ladder ascending to heaven, which would consist of twelve component communities surrounded by a wall which would gather sunlight to prove energy. He advocated a new type of intellectualism he called biocosmology, which would allow humans to "clearly see the relationship between the whole and the particulars of daily life".[94]

Although the concept of building solar cities got little traction, there was interest and government funding for solar energy in the wake of the second oil crisis and growing fear that Middle Eastern oil supplies might be cut off from Israel. Goldman formed LUZ International in partnership with an entrepreneur called Patrick François, a French-Israeli dual national. They drafted a business plan and traveled to the U.S. looking for venture capitalists to invest in their project. Goldman and François decided to base LUZ's R&D and manufacturing in Israel. However there was little interest in investing in solar, and even less in investing in a foreign company. Goldman then went back to the investors who had supported his earlier, word processing company, and appealed directly to the Jewish community. With funding, Goldman built a small solar energy collecting with a computer control system to keep it aimed at the sun, which produced steam and heat. A small industrial process-steam generator was built for a kibbutz in Israel. When this worked, LUZ started building three pilot industrial steam systems for textile companies in the southeastern United States. It turned out that this plan was not viable. The locations with the best sunlight, like Californian deserts, had no industrial facilities which needed steam, whilst the areas with factories often had less sunlight.[95]

PURPA, or rather the state of California's energetic execution of it, salvaged the business. After learning that a subsidiary of Phillips Petroleum, which was also in the process steam market, obtained a contract from a utility, the Southern Californian Edison Company, to sell it power, Goldman decided to refocus on that market. Between 1984 and 1990 LUZ raised a $1 billion and built nine reflective solar collectors in the Mojave desert, which focused sunlight on oil-carrying receiver pipes. The oil was heated as it circulated through the pipe to create the steam for turbine generator. LUZ sold its electricity using the feed-in tariffs, and earning returns for its investors through careful use of tax credits.[96]

Other types of solar business also developed in California. David Katz was an electrical engineer who worked for the Navy for a few years as a civilian technician before joining the "back the land" trend and moving to a community in northern California near San Francisco. His house was off the grid, and to generate electricity he experimented with putting extra batteries in his car which could be charged as he drove. By accident, he encountered solar energy. As he later recalled,

"I was at the Consumer Electronics Show in Las Vegas in 1980, and there was a guy selling solar toys. He had one solar panel in the booth. I bought 100 and went back to northern California and sold them all in a couple of days. Now you didn't have to have your car. For a couple thousand dollars, you could have lights and music in your house."[97]

He founded Alternative Energy Engineering to sell solar devices to people who lived beyond the electric grid. By the mid-1990s, the company published a hundred-page catalogue and built new headquarters made of recycled redwood and steel. The company claimed to stock the largest variety of equipment for making and efficiently using electricity anywhere and shipped its product around the world.[98]

Other young entrepreneurs, attracted by the alternative lifestyle, also invested in solar. Wayne Robertson was one of them, a licensed lumberer, and a son of two police officers in Los Angeles, was eager to escape the city life and bought a piece of property with his wife in a secluded area in Northern California. That's when he gained interest in solar. As he later recalled, "I was living about 12 miles off the grids, so we used to plug our vehicles in different things to create power and to run our homes. So solar was just a natural progression, a natural thing to happen, and you know most of the people living in these hills were highly educated folks who didn't want to use fossil fuels, they were looking for an alternative source of power, so this is really what got us started."[99]

Robertson after experimenting for years in his backyard with solar panels, he launched with the financial backing of a friend Solar Electric Specialties (SES) in 1981, retailing solar panels (manufactured by ARCO and Solarex) to off-grid costumers with alternative lifestyle. Within a couple of years SES controlled most of the U.S. western market selling almost exclusively to alternative lifestyle costumers "I started thinking about a smart way we could use and sell these PV panels, and where I lived, there was a lot of people who living off the grid and with a similar mindset as us (…) there were also marijuana growers living around that had lots of money and were willing to try new things (…) those were our first clients".[100]

By the end of the 1980s the financial record of the US solar industry was decidedly mixed. In California, small niche businesses like those of Solec, and Katz and Roberston, were profitable. Luz has also made successful use of tax concessions and PURPA. The large investments by oil companies had created substantial enterprises. In 1993 Amoco-owned Solarex and Siemens Solar (the formerly Arco-owned Solar) were the dominant forces in the US PV industry, accounting for 84 per cent of US shipments and 31 per cent of the world shipments.[101] They had not, however, turned solar energy into a profitable business, certainly compared to the profits that could be earned in the petroleum industry, though they had made life difficult for smaller firms trying to build solar energy businesses.

US companies had led the commercialization of PV technologies. The technology had emerged from Bell Laboratory, the postwar American powerhouse of innovation. It had been developed by semiconductor manufacturers, another industry in which the Federal government had taken a lead. These and other firms invested initially primarily because of government demand for PVs for the space program. Government demand was expanded through the programs to stimulate renewable energy from the 1970s, both at the Federal level and in states such as California. This attracted new entrepreneurs into the industry. As the costs of further technological development rose, a further set of deep-pocked American firms bought up entrepreneurial firms and took the technology to the next level. However deep pockets proved no solution to make the technology profitable.

Collapse and Renewal of the US Industry

As in the case of wind energy, solar energy was always vulnerable to shifts in the price of alternative fuels, and to often related changing public policies. During the 1980s both factors eroded the conditions which had favored the spread of solar in the previous decade. The world price of oil, which had peaked in 1980 at over US$35 per barrel, fell to $10 per barrel by 1986. The price of oil and natural gas, remained far below previous heights for the following two decades. This coincided with ideological shifts in the United States which resulted in reduced support for renewable energy.

The election of Ronald Reagan as President in 1980 brought the Carter solar program to an abrupt end. During fiscal year 1981 the Reagan Administration cut solar funding by $79 million and reduced the solar energy budget to about $193 million for fiscal year 1982, in favor of nuclear. Reagan rejected recommendations of the Solar Energy Research Institute suggesting that the United States could implement a program to increase the share of renewables in energy production. The staff of SERI was cut from 950 to 350.[102] The vocal support for solar of environmentalists and anti-nuclear activists, like the actress Jane Fonda, was a liability in the new political context, as solar was in effect politicized within the American political system.[103] Solar tax credits initially escaped the budget axe. These credits include a 40 per cent residential credit for homeowners on the first $10,000 invested in solar equipment and conversion, a 15 per cent residential credit for landlords, a 15 per cent business investment credit, and a tax credit for industrial development bonds for state renewable resource programs. In 1985 most of these credits were ended apart from the business solar investment credit which continued until 1988.[104] Meanwhile, the Republican governors who succeeded Jerry Brown in the state of California after 1982 also began to close down credits and subsidies.[105]

. The changing price of oil, and shifts in public policies, resulted in divestments and closures. This risk was understood by entrepreneurs at the time. Varadi later commented on his own policy towards Solarex,

“We never relied on government money or programs, we were constantly going after costumers, where the real money is. For example Solar Power Corp, who was our main competitor when we started, had to shut down because they were depending on federal funding and the government was also their main costumer. We made it a point to not work exclusively with government agencies at Solarex."[106]

Among those affected by the sudden downturn in the solar market was Stanford V. Ovshinsky. He had invented an automated lathe in the 1940s, and launched into a career in inventing focused on the use of amorphous materials, which include combinations of cesium, tellurium, germanium and other elements. He and his wife set up a company called Energy Conversion Devices in 1960. During the following decade Ovshinsky became interested in PVs, and began working with cheaper materials than the expensive silicon crystals used at the time. In 1977, his work with these materials led him to begin work on a machine that would make a paper-thin film of PV. The Ovshinsky's planned a factory that would make such thin-film solar PV. Ovshinsky envisioned a machine that would deposit layers of the electricity-producing film on flexible materials, such as stainless steel, plastic membranes and even shingles. He struggled to interest investors, but in 1980 Atlantic Richfield invested $25 million in a three year contract. In the context of the Reagan cuts to solar budgets, this contract was not renewed. As funding sources dried up in the United States, Overshinsky went offshore. He formed a joint venture with the Japanese electronics company Sharp, in which Standard Oil of Ohio also took a 5 per cent share. A plant was opened in Japan.[107]

Solar companies in the United States became pawns in the market for corporate control, as one owner who had failed to make the business profitable sold it on to another. Increasingly, as in the case of Overshinsky, entrepreneurs looked abroad. In 1984 Exxon sold the Solar Power Corp. to Amoco-owned Solarex. Arco sold its solar business to Siemens in 1990, by which time it was largest PV manufacturer in the world. Andersen had retired from Arco by this time, and his successors justified the sale on the grounds that they had invested $200 million in solar energy but it was still not profitable.[108] Five years later Siemens sold the business to Shell. Mobil also sold its solar business to German-owned ASE in 1994.[109] In 1994 Shahryar sold control of Solec to two Japanese firms, Sanyo and the Sumitomo Corporation, originally staying with the company, and then in 1996 founding a new company, the Solar Utility Company in Los Angeles. In 2002, Shahryar sold his company in order to volunteer as the Afghan ambassador to the United States. He was the first Afghan ambassador in 23 years for the United States, representing the government of Hamid Karzai for one year. [110]

The changing environment also resulted in the end of LUZ. The company had uniquely, for a solar company, survived during the Reagan decade. By 1990 it had built and installed nine solar power stations in California. For the tenth project it hoped that investors from previous projects would continue as before. However, LUZ had previously been exempt from Californian property tax, and this exemption suddenly stopped. It was a fatal development. In the words of Goldman ,

“Solar and other renewable energy plants require working in a zero, or at least very low, property-tax environment in order to be economic. Solar - or wind - energy is basically a fuel substitute. Like fuel, what solar thermal does is heat up water to make steam, which makes electricity. Unlike fuel, such as coal or gas or fossil - which when burned goes into the air, and therefore does not require property tax - solar energy requires a huge amount of solar-energy heat-producing equipment. In fact, large solar plants can have billions of dollars' worth of solar equipment. Equipment is considered "assets." And assets - unless expressly exempt - require property tax. Still, we decided to try to build the 10th project, because approximately 90 per cent of the California State Assembly favored extending the property tax exemption. But, in his last few minutes in office, governor George Deukmejian vetoed the legislation, and this made it impossible for us to finance the 10th project. ….it was absolutely ridiculous. [111]

LUZ International filed for bankruptcy in 1991.

Japan and Europe

During the postwar decades both Japan and Europe lacked both the huge space program and the governmental investment in renewables during the 1970s which had driven the growth of the American PV industry. As a result the investment in the industry relied less on the prospect of government contracts, and more on the potential of solar for commercial use. In both regions, the development of PV technology was led by electronics firms. As the American solar industry spluttered, a powerful new source of growth appeared, especially in Japan and Germany, as governments engaged in massive programs to subsidize rooftop PV systems. By 1988 European and Japanese owned firms dominated PV production. (see Appendix Table 5)

In Japan, the solar industry was created and shaped by electronic corporations based in the Kansai region, at a considerable distance from Tokyo, and with a tradition of independence from the Japanese government bureaucracy based in Tokyo. The pioneer venture was Sharp. This company originated before World War 1 when it was founded by Tokuji Hayakawa as a metalworking shop and a vision to make people happy. The company pioneered the Japanese production of radios during the 1920s, and after World War 2 diversified into televisions. In 1953 it launched the first commercial television set, and over the following years also made refrigerators and washing machines. In 1961 Sharp began to invest in new product development in electronics, and this took the firm into electronic calculators, optical semiconductors, computers and solar cells. Sharp's engineers focused on developing marketable applications for solar cells. This led to use of Sharp solar cells in the No. 1 Tsurumi light buoy in Yokohama Port in 1963.[112]

As Sharp developed the world's first electronic calculators, and then office products during the 1970s, it continued to invest in PV as a modest part of its business portfolio. Japan's modest space program provided some market for Sharp's products. In 1976 the Japanese satellite "Ume" was launched with Sharp's solar cells on board. However Sharp's primary focus was commercial applications. In 1976 Sharp also introduced the world's first solar-powered calculator. In 1979 the company built a hybrid house powered and heated by solar panels at its R & D facility near Nara. None of these activities generated profits, and the continued investment appeared to have been motivated by the personal vision of Hayakawa. "I believe the biggest issue of the future is the accumulation and storage of solar heat and light," he wrote in his 1970 biography "while all living things enjoy the blessings of the sun, we have to rely on electricity from power stations. With magnificent heat and light streaming down on us, we must think of ways of using those blessings. This is where solar cells come in."[113] In 1982 Sharp entered the joint venture with Stanford Ovshinsky's Energy Conversion Devices, but that was wound up in 1987. [114]

A different approach was taken by the Kyocera Corporation, which was founded as Kyoto Ceramic Co., Ltd. in 1959 by Kazuo Inamori. Kyocera's original product was a ceramic insulator known as a "kelcima" for use in television picture tubes. The company quickly adapted its technologies to produce an expanding range of ceramic components for electronic and structural applications. In the 1960s, as the NASA space program, the birth of Silicon Valley and the advancement of computer technology created demand for semiconductor integrated circuits , Kyocera developed ceramic semiconductor packages. In the mid-1970s, Kyocera began expanding its material technologies to produce a diverse range of applied ceramic products, and invested in solar.

Inamori's interest in solar had its origins in his growing awareness of environmental problems. Japan's rapid industrialization during the 1950s and 1960s resulted in growing pollution. Inamori noted that the water from his own factories polluted rivers and killed fish, and by the late 1960s he was already investing in water purification technology, even though it forced up the costs of his still medium-sized company.[115] These environmental issues led him into solar after a fortuitous encounter with a new technology in the United States. As he later described,

> "From various media articles, I knew that some companies such as Sharp and US companies had been developing solar cells and that solar power was, though weak, a most ideal alternative energy source. Japan had no energy sources and had to import everything including coal, oil and natural gas, and I thought it was a weak point of the nation. …I became friends of a president of Tyco, a venture company based in Boston. I learned that Tyco had successfully developed a technology to pull out a single crystal sapphire – being a ceramist I had some expertise in crystallization of minerals. When I heard about this, with this technology, I thought it would enable to create various shapes of sapphire."[116]

Inamori's encounter with Tyco came just as the oil shock was hitting Japan, and he realized the implications for making solar cells.

> "Till then, solar cell was produced by pulling out single crystal silicon in a cylinder shape and slicing the silicon cylinder into pieces, like creating wafer for semiconductor. But Tyco people told me that if using their method there would be no need to make silicon in a

> cylinder shape and no need to slice it. They said they would be able to produce solar cells much less expensively by pulling out silicon in a film form."[117]

He considered producing solar cells using the method, but concluded that mass production could not be done by a single company. He then contacted the heads of Sharp and Matsushita, leading electronics companies, and they set up the Japan Solar Energy Corporation.[118]

The Japanese government, like the US government, became interested in solar energy after the oil shocks. In 1974 Project Sunshine was launched to explore alternative energy sources. This turned out to be at best ineffective, for the focus was on solar thermal energy, while Japan had frequent cloudy skies.[119] At worst the government programs were environmentally damaging, as the ocean thermal energy conversion technology developed by the Project facilitated stratospheric ozone depletion.[120] Although Project Sunshine sponsored considerable R & D into renewable energy, the government also made no effort at all to translate research into actual products. The Japanese government's reaction to the energy crisis was to work towards securing stable oil supplies, and to promote the development of nuclear power, which it insisted was a clean energy source. There were yet further obstacles because the country's ten electric companies monopolized the energy market, and had no interest in solar, wind or another renewable energy.[121]

The futility of Japanese energy policy was fully recognized by Inamori, who was concerned to keep his distance from government. As he later described,

> "After the oil shock, the Japanese government launched the "Sunshine Project" to promote solar cells. But as my basic assumption is that what the government offers is usually not good, I was not interested in the project and did not participate. We had a challenge that we could not find any demands though we had made some products."[122]

Inamori mobilized his engineers at Kyocera to work on the development of solar cells, but it proved a lengthy and costly process to pull out silicon in a film form by a roller. The company also tried to think of ways to develop a market, developing various products such as solar-powered batteries for portable radio and road signs. In 1979 the company got its first large order, which was for panels to power a microwave telecom relay station located in the Peruvian Andres.[123] As the memory of the oil shocks faded, and costs stubbornly refused to come down, the solar joint venture stumbled, and Kyocera remained the sole owner. Inamori again found a foreign technology which could help. Wacker, the German electronics company, had a developed multi-crystal silicon wafer. Inamori scraped all his firm's existing production facilities and shifted to multi-crystal approach which produced silicon ingot by molding, which would in time become a major production method for solar cells. The Shiga Yohkaichi Factory was established in 1980, and manufacturing of solar cells started with mass production of multi-crystalline silicon solar cells two years later. In 1993 Kyocera achieved a 19.5 % world record efficiency with single-crystal silicon solar cells.[124]

> Meanwhile, Inamori took a lead in developing a new market for solar. As he later described, "I thought that in order to create demand, solar panels for houses would be most influential. Utility companies had firmly opposed to the introduction of solar panels to individual houses. Therefore, I organized the Japan Photovoltaic Energy Association in 1987 involving solar cell manufacturers such as Sanyo, Matsushita, Sharp and Kyocera, and started to lobby the government for allowing and supporting houses to install solar cells."[125]

By then a third Kansai-based electronics company, Sanyo, had also developed a large solar business. It also employed solar cells in its calculators, but did not use crystalline silicon but thin film technology. This was not as efficient converting sunlight into electricity, but performed well when applied under electronic light. The huge growth of the solar–powered calculator market resulted in Sanyo emerging as the world's largest solar cell manufacturer by 1986.[126]

The lobbying of the Japan Solar Energy Corporation eventually produced results. In 1994 the Japanese government, heavily influenced by a German program introduced two years previously, launched the Ten Thousand Roofs Program under which the government paid one-third of the installation cost for household roof—mounted PV panels; funds for the program were collected through an electricity surcharge. Local electric utilities had to purchase excess power generated by the PV systems at the retail price of electricity. In 1997 another law, the Law on Special Measures to Promote Use of New Energies, provided further subsidies. Although Japanese government remained stubbornly attached to fossil fuels and nuclear power, the new laws provided a more favorable context for solar energy. Over the following years Japan became the largest solar cell producing country in the world, accounting for 40 per cent of world production. Between 1992 and 2000 the number of rooftop solar systems expanded from 1 to 50,000, but most of the PV production was exported. Sharp, Kyocera, Sanyo and Mitsubishi, grew to be among the top ten PV manufacturers in the world.[127]

In Europe there was, as in Japan, an early interest in the potential of PV solar energy. As in Japan, this interest was primarily found in electronics companies. During the second half of the 1950s Kees Daey Ouwens, a young engineer at Philips, the leading Dutch electronics company, did experimental research on solar cells, powering a transistor radio with one in the garden of the physics laboratory of Philips. However interest in the technology waned after the discovery of the large gas field at Groningen in 1959. During the 1970s Ouwens continued to work on solar at Eindhoven University, despite attempts to silence criticism of nuclear energy by supporters of renewables, and the University hosted conferences on renewable energy, especially its use in developing countries. In 1981 a Dutch company, Holecsol, was founded to produce solar cells, which was acquired by Shell in the following year.[128]

In Germany, too, the electronics giant Siemens was interested in solar from the 1950s. The first achievement by Siemens was the production of ultrapure monocrystalline silicon using zonal heating. This innovation was followed by the invention of a reactor, a thermal decomposition furnace, which enabled the production of polycrystalline silicon. Both technologies became widely used in the semiconductor and PV industries. [129]

As elsewhere, the oil price rises of the 1970s increased interest in several European countries on alternatives to fossil fuels. In France, as in the United States, the government became engaged in solar energy research. In 1975 the CNRS, the state research agency, built a 1000-kw solar furnace at Odeillo, the world's largest, high up in the French Pyrenees, while the French space agency began research on thin-film solar cells in Toulouse.[130] French oil companies also looked at the solar industry. CFP, the largest French oil company, began investing in solar energy research in 1975, along with a US firm, Photon Power, but this was soon abandoned. In 1983 it returned to solar by establishing Total Énergie in Africa with a mission to develop renewable energy resources. It began manufacturing solar modules in South Africa in 1996, and by the end of the decade had acquired large franchises in Morocco, and developed a European business.[131] The firm of Photowatt was established by Elf Acquitaine, another oil company, and Compagnie General des Eaux, a utility company, but this struggled also until a scientist, Claude Rémy, took control in 1979.[132] It moved into the US market and by 1982 had a production facility in Phoenix, Arizona.[133] By 1988 it accounted for about 2 per cent of world production, and was ranked in the top nine solar firms (see Appendix Table 5).[134]

In Italy, there was considerable scientific interest research in solar power, associated especially with Giovanni Francia's experiments with concentration type solar thermal employing flat mirrors. Ansaldo, the large electrical machinery company, began PV production during the 1970s, although subsequently withdrew because of unprofitability. The national electric utility ENEL built the world's first large concentrating-type solar plant in Sicily in 1980, but it was closed down after some years of tests.[135] There were also start-ups. In 1981 Helios Technology was founded near Padua by Franco Traverso to manufacture PVs. He was a mechanical engineer, whose father owned a small plastics company, who became "fascinated by the idea of producing energy from the sun." He met a professor from the University of Padua, who worked in silicon technology and had contacts in the United States which provided the technology for the new venture. Traverso sought his first customers among the owners of country houses in remote rural areas where solar power offered a solution as a source of electricity, and used residues from the semiconductor industry as raw material before inventing a means to recover silicon from used electronic devices.[136] Helios was one of the world's top nine solar producers by 1988, albeit with a small output. (see Appendix Table 5). Six years later Photowatt held 2.6 per cent of the world market, and Helios 1.4 per cent.[137]

On a smaller scale, small firms were also founded in Spain. A socialist government led by Felipe Gonzales from 1977 to 1982 took some legislative steps to promote renewable energy, although allocated few financial measures. It did seem to stimulate some interest in the solar business. In 1981 Isofoton was founded in Malaga out of a university project led by a professor from the Polytechnic University of Madrid build PV cells from silicon wafers technology. In 1983 the firm Atersa was created as a result of the merger four years previously of two small solar distributors. It developed a small manufacturing business which included installation of PV systems to provide rural electricity and water pumps and public lighting systems. In 1984 the long-established engineering firm of Abengoa, based in Seville, which had provided equipment for electricity grids, built some of the components for a solar platform, which began a growing investment in the industry. Felipe Benjumea, the son of the founder, started working in the company in the early 1980s, and had developed an interest in environmental issues, particularly global warming. He decided to invest in renewable energy, and to make "greenness" the new core philosophy of the company. Absent of government support, however, the business was largely abroad, begin with a contract for equipment for the Weizmann Institute of Science in Israel. [138]

In Britain, where an official report had been skeptical about the prospects of solar energy as early as 1952, the oil crisis revived interest. The country's Department of Energy commissioned a study on the potential of solar energy, which was published in 1976. It concluded that if sufficient investment was made, it was possible to envisage solar energy contributing 2 per cent of the country's energy needs within 25 years.[139] However momentum was quickly lost as the discovery of oil and gas in the North Sea accelerated. BP found gas off the coast of East Anglia in 1965. Ten years later the large Argyle and Forties oilfields were discovered. By the early 1980s Britain had become a net exporter of oil, and by the mid-1990s of gas. The government, controlled by the right-wing Conservative Party between 1979 and 1997, had few concerns about either the environmental effects of fossil fuels or the security of energy supplies.

It was Germany which became the first European country to adopt a formal renewable energy policy. This originated in 1974 and was primarily initially focused on research. Government spending on solar began modestly, given that boosting nuclear and coal production were the core priorities. The equivalent of EUR10 million was spent on solar energy in 1974. This had risen to EUR60 million in 1978, and peaked at EUR150 million in 1982.[140] The Chernobyl accident in 1986 had a huge impact in Germany, and stimulated increased support for alternative energies. In 1990 the government launched a 1,000 roof program for PVs under which the federal government provided 50 per cent of the investment costs plus a further 20 per cent from the state (Lander) governments. Some 2,250 roofs were equipped with PV modules. In 1991 a feed-in-tariff was introduced which required utilities to connect alternative energy generators to the grid, and buy their electricity at agreed rates set at 80 per cent of the historical average retail price. The program was capped at 5 per cent. This provided incentives to investors, although less for solar because of its high expense. The feed-in tariff rates were under the cost of producing PV cells, although several Lander continued to support solar installations for special purposes, like schools.[141]

The German policy for renewables provided the context for the further investment by Siemens in the solar industry. In the early 1980s, Siemens was part of the first terrestrial application of solar power, participating in a European Union project to install a solar power plant using monocrystalline solar cells on the Greek island of Kythnos. Siemens developed the first thin-film technology based on hydrogenated amorphous silicon. In 1990 Siemens acquired Arco Solar, taking over its investment in thin film technology based on copper indium diselenide. The size of the German market could not match that of the American at that time, and Siemens proceeded to close down its domestic production in favor of its American plants, and focused on supplying markets in the developing world. By 1996, based on crystalline silicon wafer technology, Siemens Solar Industries accounted for one-fifth of the total installed PV capacity worldwide, at the time equal to 100 megawatts.[142] The other two manufacturers in

Germany were divisions of other big companies, Nukem – a uranium services company – and DASA, an aerospace company. In 1994 these firms spun off their solar divisions to form a new company, Applied Solar Energy (ASE).[143]

Although the German policy regime for solar and renewable was modest compared to what would come later, it contrasted with that followed in other European countries, which was even less supportive of renewables. In Britain, for example, support for renewable energy began almost accidently in 1990 with the Non Fossil Fuel Obligation (NFFO). This was a device established to provide financial support for nuclear power when the British electricity system was privatized, and was funded from a levy placed on all consumers. The newly privatized Regional Electricity Companies, or RECs, were obliged to purchase power from generators at a premium price, and renewable energy such as solar and wind got included in the arrangement. The levy receipts were used to reimburse the RECs for the difference between this premium and the average monthly 'pool' purchasing price. Developers were invited to submit competitive bids for NFFO contracts. This auction system, which was quite different from feed-in-tariffs, and primarily designed to force down costs, lasted for two decades. It proved more of a problem than an opportunity for renewables. Tendering in successive rounds created batches of parallel projects. The system also encouraged gaming as there was no penalty for companies who won at auction but did not take up a contract, which encouraged firms to bid low simply to prevent competitors from securing contracts. Both the complexity of the planning process, and the uncertainties of success, deterred entrepreneurial entrants, which differed considerably from the German experience.[144]

In Germany, the structure of electricity distribution, which was privatized in 1998, facilitated further experimentation with solar energy. Four large companies - E.ON, RWE, Vatenfall and EnBW – generated four-fifths of the country's electric power, while the remainder was generated by a thousand or so local electric utilities, typically owned by the towns which they served.[145] This structure provided an opening for local environmental activists to lobby city councils for a system whereby the private owners of solar systems could feed the electricity they generated into the public grid, receiving sufficient in return to maintain their systems and make a small profit. After several towns had taken this route, it was approved by the government of the Lander of North Rhine-Westphalia in 1994, and then spread. By 1997 forty two German towns had such systems.[146]

These events provided a backdrop for new measures following the election of a new Federal coalition government composed of Social Democrats and the Green Party in 1998. A new 100,000 roof program was in place between 1999 and 2003. The Renewable Energy Sources Act in 2000 established a revised feed-in-tariff regime which, among other measures, fixed rates for 20 years. This Act decoupled feed-in tariff process from retail rates and instead based process on the cost of production. The cap on renewables was removed.[147] The profit incentive for houses to adopt solar systems worked as an effective inducement. By 2008 an estimated half a million German roofs had solar systems.[148] Critics complained that the promotion of solar industry in a country with the same amount of sunshine as Alaska made limited sense. They also noted that it was richer people, whether house owners or farmers, who could put solar panels on their roofs, while the less affluent who lived in apartment blocks simply got higher electricity prices.[149]

While in Japan the growth in the solar market spurred the growth of existing PV manufacturers, this did not happen in Germany, nor in Europe as a whole. Instead, a new set of entrepreneurial actors emerged. In 1996 Reiner Lemoine founded Solon. Lemoine was an aerospace engineer, with an early commitment to radical ethical and environmental issues. He had founded an engineering company in Berlin called Wuseltronik after graduating in 1978 which built measuring devices for wind and solar applications. It was run as a collective, and on the basis of high ethical principles, which included refusing to accept contract work from the army. In 1996 he co-founded another company, Solon, to assemble PV modules, which two years later became a public company, with the corporate slogan “Don’t leave the planet to the stupid.” It was initially planned for Solon to make solar cells in its own factory in Berlin, but Lemoine could not raise sufficient capital. After finding that the solar cells which it then had to acquire from outside suppliers were of variable quality, Lemoine and his colleagues left Solon to form their own specialist cell manufacturer, Q-Cells. This was an innovation in the traditional PV industry structure, which had always seen companies combine wafer manufacture, cell production and module assembly.[150]

Q-Cells was one of several German solar start-ups. Solar Millenium was founded in 1998 in Erlangen, Germany, and focused on the design and implementation of solar thermal power plants. SolarWorld was launched as a company in 1998, this time in Bonn, as a business run by Frank H. Asbeck, was one of the founders of the Green Party in Germany, and had started up an engineering bureau for industrial plants ten years previously. One of its businesses was renewable energies. SolarWorld began as a distributor of solar modules. It went public in 1999 and began building its own production facilities. One year later, it bought the chemicals and pharmaceutical giant Bayer's solar energy unit in Freiberg.[151]

The German solar boom also attracted established companies. Schott, a long-established glass and ceramic manufacturer, had had a small interest in PVs since the late 1950s. In 2001 it entered the sector on a larger scale. In 2002 it acquired a 50 per cent share of RWE Solar, the former ASE, and took complete ownership three years later, which made it one of the top ten PV manufacturers in the world. In contrast, in 2000 Siemens put its solar interests into a joint venture with Shell and the German electrical utility E.ON. In the following year Shell Solar acquired all of Siemens Solar.[152]

As in the United States, although somewhat later, European oil companies had become interested in solar energy during the 1970s as they pursued the then fashionable strategy of diversification. In 1973, Shell moved into nuclear energy by forming a partnership with Gulf Oil to manufacture gas-cooled reactors and their fuels. The initial cost was a hefty $200 million, but Shell quickly discovered that the political problems of the oil industry were multiplied in the nuclear industry, particularly after the accident at Three Mile Island in the United States in 1979. The following year Shell sold its interests. During the 1970s a large coal business was also acquired by Shell. This business also proved volatile, and was abandoned during the late 1990s.[153]

Shell's early steps into renewable energy were more modest. It entered solar heating with the acquisition of a 50 per cent interest in an Australian company Solarhart in 1979. This Perth company, originally a plumbing and ironworks venture, had developed a solar heating business in the 1950s, and built a nation-wide dealer network selling solar water heaters.[154] Two years later Shell acquired the Dutch company, Holecsol. In the same year Shell's distributor in Japan, Showa Oil, entered the solar business, and this became a significant part of Shell's Japanese business when it consolidated its businesses in that country in 1985 to form Showa Shell Sekiyu K.K.[155] In 1997, as the withdrawal from coal approached, Shell ramped up its renewable investment by establishing a new core business, which it publically announced that it planned to invest half a billion dollars in over the following five years. Shell's activities in solar power, biomass power and forestry were consolidated in a new organization, Shell International Renewables. In 1999 wholly owned subsidiaries were established in solar energy systems in India, Sri Lanka, and the Philippines, targeted at rural electrification programs, and solar home systems were introduced in South Africa. In the next year Shell opened another solar-panel manufacturing operation in Germany, in a joint venture with the British glass company Pilkington, to add to its plants in the Netherlands and Japan. The firm's Annual Report in 2000 announced the explicit strategy to become a global leader in Renewable Energy. By then Shell was the world's fourth largest supplier of solar panels in a market which is growing by around 25 per cent a year.[156]

BP, Europe's other major global oil company, also entered solar energy. In 1981 it formed a solar joint venture with the British engineering company Lucas Industries, and it acquired full-ownership in the following year. In 1986 it acquired Standard Oil of Ohio, which had an investment in Ovshinsky's amorphous materials and thin-film technology, but the British company opted to end the relationship and instead focus on commercializing silicon crystal panels instead.[157] By 1994 it was the second largest European-owned PV manufacturer after Siemens, holding the third largest world market share. While Siemens dominated with 20 per cent of the world market, Solarex held 9.7 per cent and BP 9.3. Sanyo, the largest Japanese company, was in fourth place with 7.9 per cent.[158] BP had been in the forefront of solar development in many countries, opening a panel manufacturing plant in Madrid, Spain, as early as 1983, for example. During the mid-1990s BP launched into that market the first 100 Kw solar panel, the most efficient panels at that time, and by 1998 the BP Solar operated in 16 countries. By 2001, when BP Solar opened the largest solar plant in Spain at that time, it had acquired Amoco, including its share of Solarex as well as that of Enron, making BP Solar the world's second largest PV manufacturer after Sharp.

By 2001, as Appendix Table 5 shows, the list of the largest PV cell manufacturers was overwhelmingly European and Asian, with US-ownership decimated. However the United States was still in second place as a manufacturing country after Japan, as the foreign firms which had acquired U.S. firms continued to operate American production facilities. In contrast, the Japanese firms produced all of their PV cells in Japan. Shell's business structure in solar was noticeably global. It had manufacturing facilities in the Netherlands, Germany, Portugal, and the US, and a sales network on all continents.

A New Solar Boom and Bust

The decade after 2000 saw a remarkable boom in solar energy, only be followed by a spectacular bust for many corporations engaged in it. The boom was driven by a renewed bout of government subsidization of solar energy as concerns about, and evidence of, climate change mounted. In Europe, the example of the German Renewable Energy Sources Act and its feed-in tariff program was followed by Spain, Italy, France and several other countries.[159] In Spain, where the level of support became the most generous, there were feed-in tariffs, government investment subsidies and soft loans, and regional authority subsidies often covered between 15 per cent and 50 per cent of total investment. Many large cities in Spain have approved regulations requiring the obligatory installation of solar PV on new buildings and some regional energy plans prioritized the use of PV.[160] By 2009 the share of electricity generated by solar in Spain was the highest in the world. (Appendix Table 1)

There were also new US policies to support solar. A slow rise in environmental concerns began under the Presidency of George Bush beginning in 1989. This continued during the Clinton Administration between 1993 and 2000, although there were few concrete measures to support renewable energy beyond an increase in gasoline taxes.[161] Clinton's successor, George W Bush, quietly installed solar systems in the White House in 2002, and three years later the Investment Tax Credit allowed businesses to invest in solar power projects and receive a tax credit for up to 30 per of the expense. As a short-term remedy to the almost annual reauthorization quest for the ITC, the Emergency Economic Stabilization Act of 2008 extended the 30 per cent solar investment tax credit for eight years to 2016, and removed the prohibition against utility company use of the ITC, thus allowing them to take advantage of the credit. There was also substantial support at the state level for solar energy. In 2007 the state of California also launched the California Solar Initiative, which offered substantial incentives to get solar panels on domestic roofs. It was joined by a group of other states, including New Mexico, Colorado and Arizona, and less sunny states such as Massachusetts and Pennsylvania.

China made a rapid entry into solar industry in order to build a presence in an industry deemed to be strategic. A Renewable Energy Law in 2005 was designed to promote the development and utilization of renewable energy, and safeguard energy security. Renewable energy was subsidized by a fee charged to all electricity users in China of 0.029 cents per kilowatt-hour. The fee was originally based on the incremental difference between coal and renewable energy, and went to the companies which operate the electricity grid and must buy renewable power from project developers. The Renewable Energy Law was amended in 2009 to require electricity grid companies to buy all the electricity produced by renewable energy generators. A “Golden Roofs” initiative also announced in 2009 provided a subsidy of $2.93 per watt for roof-mounted PV systems over 50 kilowatts which could cover over half of a system’s installation cost. A feed-in tariff of $0.16 per kilowatt-hour was also established for PV power projects at the same time. Encouragement for larger utility scale solar projects was announced in the same year under the “Golden Sun” program, which provided for up to 50 per cent of project costs, and up to 70 per cent of such costs for projects in more remote areas. Provinces also provided local incentives for solar development.[162]

None of these measures meant, however, that much Chinese electricity was generated by solar. As Appendix Table 1 shows, solar remained an inconsequential source of electricity. In the big picture, the Chinese government believed that solar was too expensive to become a major solution for Chinese energy requirements, and in so far as the government seriously promoted renewables, the focus was on wind and biofuel.[163]

The growth of subsidies resulted in a surge of growth in PV installation and manufacture. (Appendix Tables 2 and 4) There was a steady fall in the price of solar cells. In California, costs were estimated to have fallen 5 per cent annually between the mid-1990s and 2006. However this still left it expensive: electricity produced by crystalline cells was estimated by 2006 to have a total cost of 20 to 25 cents per kilowatt-hour, compared with four to six cents for coal-fired electricity, five to seven cents for power produced by burning natural gas, and six to nine cents for biomass power plants.[164]

The solar boom resulted in significant structural shifts in the industry. The first was the emergence of specialist polysilicon manufacturers. Polysilicon prices soared until a sudden crash in 2009 in the wake of the financial crisis. The market was controlled by a handful of large corporations, with seven firms accounting for roughly three-quarters of polysilicon production.[165]

Secondly, there were major changes in the ownership of PV manufacturing. The solar boom stimulated the rapid growth of entrepreneurial specialist solar PV manufactures. By 2006 the recently founded Q-Cells was the second largest producer in the world after Sharp, and ahead of Kyocera. It attracted large financial backing from venture capitalists, beginning with Good energies, an affiliate of the investment business s of the Brenninkmeijer family, the owners of the C & A retail chain.[166] The company's market valuation reached $10 billion in 2007. Other German start-ups including Solon, Solar Millennium and Solarhybrid grew rapidly. During the first half of the decade the estimated return on investment in the German solar power industry was between 10 and 13 per cent.[167]

In the United States, there was also renewed growth by local firms, who often initially supplied the booming European market. The leading U.S. firm was First Solar, an Arizona company which had been started by the inventor Harold McMaster, who formed Solar Cells, Inc in 1990 with the aim of making thin film cells on a large scale. In 1999 it was purchased by True North Partners, LLC, the investment arm of the Walton family, who owned WalMart, who rebranded it as First Solar. The company grew rapidly on sales to Germany, and went public in 2006. There was also a new wave of start-ups in the United States. In 2005 Solyndra launched, supported by $1 billion of private equity funds, and employing a strategy to use cylindrical cells, rather than flat PV solar panels. In 2009 the company received a $535 million loan guarantee from the Federal government in the stimulus package after the financial crisis.

The most spectacular change was the rapid entry and growth of state-owned Chinese firms. While the Chinese government was lukewarm at best about the prospects of solar energy inside China, it was strongly supportive of the growth of Chinese firms in the global industry. It provided Chinese firms with both low interest rate loads and favorable deals for land to buy factories. The firms themselves were effective at acquiring new technologies, often using their initial position as original equipment manufacturers to Western firms to gain knowledge and market know-how. The Chinese firms were highly internationalized, selling most of the production internationally. They were bought foreign companies; in 2006 Suntech acquired two-thirds of a Japanese company, MSK, which held a 5 per cent share of the Japanese solar market. By 2011 the list of the largest PV manufacturers in the world was dominated by Chinese firms led by LDK Solar and Suntech.[168]

In contrast, the falling prices of solar cells and the entry of Chinese manufacturers encouraged the exit of the big European oil companies out of the industry. In 2006 both Shell and BP were still amongst the top ten PV manufacturers. However Shell had already begun divesting from solar in the previous year. In 2010 the firm's chief executive noted regarding the firm's investments in renewables:

"We need to grow in areas that are profitable and match our core skills. I saw thousands of Dutch shareholders recently [at an annual shareholders convention] and I asked them if they wanted wind power or a financial return. The answer is clear! That's one of the problems – I'm open to critics, but I have a business to run, and the purpose of a business is to achieve returns, to achieve long-term sustainable growth. As part of that we are prepared to invest in Research & Development, including in alternative energies. But our activities need to give us profitability. We're a company like any other and we need to make a profit in order to exist."[169] In 2011 BP followed Shell by announcing its withdrawal from the industry.

Beginning with the start of the global financial crisis in 2008, the PV manufacturing business came under severe stress from three sources. First, the growing availability of natural gas and other fossil fuels sharply reduced the perceived urgency for investment in renewable energy. In particular, new techniques such as “fracking” and horizontal drilling triggered a production boom in natural gas which promised plentiful low-cost power and energy independence for decades in the future. The discourse about the potential of natural gas was not unlike the discussions fifty years previously about nuclear energy, and in both cases environmental downsides were not articulated in the early stages. Fracking had the potential to pollute ground water and even trigger earthquakes, but there was little doubt that the availability of abundant and cheap natural case made the case for supporting renewable energy harder to make. This was especially because the momentum behind concerns about climate change had waned once more, despite a strong consensus among scientists that such change was happening. The specifics of the nature of such change remained insufficiently inexact for governments to feel comfortable to prioritize responding to more immediate financial and economic pressures.

Second, the business models of the major Western PV manufacturers were disrupted by falling prices as capacity increased, especially but not only driven by low-cost Chinese firms. In 2011 the price of solar panels fell by almost one-half. In 2011 many US solar companies went bankrupt, including Solyndra and Evergreen Solar, which had developed a novel string ribbon technology to use silicon more efficiently, which it had struggled to commercialize, despite large subsidies from the state of Massachusetts.[170] However this crisis did not deter deeper-pocketed firms from continuing to invest. During 2011 and 2012 GE invested an approximate $1.4 billion in solar energy as part of its renewable energy business. By that year GE had investments in solar projects worth $5bn across Australia, Canada, Italy, Portugal, Spain and the United States, and was also building what would be the largest US solar panel factory, a 400-MW solar plant in Colorado.[171]

Third, the crisis in the Euro currency area after the global financial crisis resulted in a sudden fall in subsidies and other support in Europe. The Spanish market for renewables fell dramatically as subsidies were reduced. In France, subsidies were frozen in 2010, and in the following year the government introduced a new system whereby only small roofs would continue to benefit from feed-in tariffs, but at a lower rate. Larger installations had to go through a complex and capped tender process. A new target of 5.4 GW of installed capacity by 2020 was ten times lower than in Germany. Photowatt went bankrupt in 2011. However, large French diversified business groups capable of cross-subsidizing renewable energy increased their investments in solar by acquiring the assets of other firms. In 2006 the French glass maker Saint Gobain acquired Shell's business in France, and five years later Total, the largest French oil company, expanded its solar business by acquiring the majority of SunPower, an engineering company which had become the second largest American solar panel maker.[172]

The decimation of the German solar industry was striking. In 2012 the German government's decision to cut the fixed price that power companies had to buy solar power from producers by up to 30 per cent resulted in Q-Cells, Solon, Solar Millenium, Solarhybrid, Scheuten Solar, and Odersun going bankrupt within a few months of each other. They were joined by Solar Millenium, which didn't even make PV cells, but rather thermal power plants.[173] SolarWorld, which had grown through acquiring Shell's crystalline silicon business and (in 2007) a large manufacturing plant in Oregon formerly owned by a Japan's Komatsu, continued in business, but the bankruptcies of so many German firms demonstrated with remarkable clarity the capability of subsidies to skew the development path of the solar industry. Subsidies created a huge demand for PVs in Germany, but they also blinkered managements from the need to shift production to lower cost sites as Chinese competition grew. Q Cells continued to manufacture in Bitterfeld-Wolfen, Germany until 2011, when it began outsourcing part of its production to Malaysia. Perversely, the German government also subsidized Chinese solar companies, according to some estimates up to €100 million, as part of development aid seeking to promote China's green industries.[174]

Concluding Remarks

In each generation, the concept of getting "power from sunshine" attracted entrepreneurial visionaries such as Aubrey Eneas, Frank Shuman, George Keck, Elliot Berman, Bill Yerkes, Ishaq Shahryar, Franco Traverso, Tokuji Hayakawa, Kazuo Inamori, and Reiner Lemoine. They were sometimes motivated by broad social and environmental agendas, including seeking to bring electricity to communities which had no access to it, and providing responsible stewardship over the world's resources and its climate.

These entrepreneurs encountered a perennial problem; solar energy was expensive compared to conventional fuels which were not priced to incorporate wider environmental costs. The invention of PV cells in the 1950s, the "space age electronic marvel," transformed the potential of solar energy, but also vastly raised the financing stakes as the new technology proved complicated, and very expensive. Niche markets were found, in satellites and pocket calculators, but the widespread use of solar to generate electricity required government subsidies and other support in a world where the environmental costs of fossil fuels were not included in pricing. This proved a huge liability.

Solar firms found themselves in a perennial dilemma. Although innovation was driven by firms, solar like other renewables needed supportive and consistent government policies to compete against conventional fuels, and to continue to invest so costs kept falling. However promoting solar, or other renewables, was seldom the top priority of governments concerned about the prices charged to consumers and economic growth, and subject to lobbying by established large vested interests with no interest in changes to the energy mix. In the United States, the space program was a key customer during the 1950s and 1960s, but this market was only for exceptionally high quality products, whilst energy policy as a whole was dominated by policies which favored fossil fuels and nuclear energy. During the late 1970s and 1980s, in the wake of the oil price rises, PURPA and state governments such as California finally offered real opportunities for renewable such as solar, but changing ideologies and falling fossil fuel prices meant that this support was not sustained. The Japanese and German PV roof policies during the 1990s were important for the growth of solar energy businesses. Government policies also explain the growth of the Chinese solar firms during the 2000s.

Governments were, however, typically fickle and regularly misguided when it came to renewable energy. US government policies were rarely consistent for any length of time, and each shifted disrupted the industry. Policies to promote national firms for strategic purposes, as in China over the last decade, were equally as disruptive for long–term development. There were only a limited number of situations, as in California in the late 1970s and early 1980s, or Germany in the 2000s, when governments and their electorates were prepared to pay more for the electricity which renewable energies produced. However these policies also encouraged rent-seeking and short-term strategies to capture financial gains, or else - as in the recent case of Germany – blinded managers to the need to respond to changing cost structures. An idealized governance structure for the development of the industry would have been internationally coordinated policies to promote renewable energy through incentives and, especially, pricing fossil and nuclear energy to include their environmental costs. There remained no prospect whatsoever of this happening in reality.

Deep pockets were necessary to develop PV technology. From the 1960s electronics and oil companies became important sources of financial and managerial resources, and they orchestrated many of the major technological developments which have led to the remarkable fall in the cost of PV cells overtime. Contrary to some conspiracy theorists, the oil companies did not invest in solar technology to block it. As one study observed, "as the hundreds of millions of dollars (the oil companies) invested demonstrate, they remained true believers for far longer than made financial sense."[175] A downside was that these large companies also made entry by more entrepreneurial firms difficult, as they were willing for long periods to subsidize heavy losses. Solar was also only a part of their portfolios. They assembled production and research assets, invested in them, and then sold them as circumstances changed. These changes in corporate ownership added to the uncertainties of an industry whose success always seemed to be just around the corner, as creative destruction became the industry norm.

Appendix
Table 1 Electricity Generation by Energy Source in Selected Countries at benchmark dates 1975-2009 (Thousands GW and % Share).

Country	Product	1975	1980	1990	2000	2008	2009
Canada	Electricity Generated	273236	367206	467733	586651	621310	585036
	Nuclear %	4.340	9.771	14.717	11.707	14.266	14.580
	Hydro %	74.074	68.353	62.837	60.525	59.664	61.596
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.003**	**0.006**	**0.017**
	Wind %	0.000	0.000	0.000	0.044	0.596	0.774
	All Combustible Fuels%	21.586	21.875	22.441	27.716	25.463	23.027
United States	Electricity Generated	1918644	2286106	3029842	3816731	4152092	3978759
	Nuclear %	8.996	10.984	19.043	19.752	19.417	20.078
	Hydro %	15.647	12.074	9.443	7.205	6.746	7.446
	Geothermal%	0.169	0.222	0.499	0.369	0.357	0.377
	Solar %	**0.000**	**0.000**	**0.022**	**0.018**	**0.048**	**0.061**
	Wind %	0.000	0.000	0.100	0.147	1.333	1.857
	All Combustible Fuels%	75.188	76.720	70.894	72.509	72.079	70.165
Denmark	Electricity Generated	17128	25173	24282	34448	34846	35448
	Nuclear %	0.000	0.000	0.000	0.000	0.000	0.000
	Hydro %	0.140	0.119	0.115	0.087	0.075	0.055
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.003**	**0.009**	**0.012**
	Wind %	0.000	0.044	2.512	12.311	19.882	19.511
	All Combustible Fuels%	99.860	99.837	97.373	87.485	80.035	80.423
France	Electricity Generated	179514	247671	401335	517887	548827	518173
	Nuclear %	9.776	23.491	74.239	76.458	76.217	75.264
	Hydro %	33.263	28.104	14.115	13.725	12.326	11.802
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.001**	**0.007**	**0.033**
	Wind %	0.000	0.000	0.000	0.015	1.037	1.523
	All Combustible Fuels%	56.674	48.206	11.505	9.691	10.321	11.283
Germany	Electricity Generated	360320	437628	509582	538489	599916	556836
	Nuclear %	6.457	12.020	28.390	29.844	23.494	22.931
	Hydro %	5.028	4.583	3.819	4.755	4.425	4.364
	Geothermal%	0.000	0.000	0.000	0.000	0.003	0.003
	Solar %	**0.000**	**0.000**	**0.000**	**0.011**	**0.738**	**1.181**

	Wind %	0.000	0.000	0.014	1.737	6.775	6.939
	All Combustible Fuels%	88.515	83.397	67.777	63.653	64.565	63.439
Israel	Electricity Generated	9068	11642	19621	40568	53021	50539
	Nuclear %	0.000	0.000	0.000	0.000	0.000	0.000
	Hydro %	0.000	0.000	0.015	0.076	0.030	0.044
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.047**
	Wind %	0.000	0.000	0.000	0.000	0.017	0.018
	All Combustible Fuels%	100.000	100.000	99.985	99.924	99.538	99.361
Italy	Electricity Generated	140935	177392	205064	263305	307065	281106
	Nuclear %	2.564	1.166	0.000	0.000	0.000	0.000
	Hydro %	30.052	26.631	16.857	19.076	15.200	18.798
	Geothermal%	1.654	1.448	1.491	1.677	1.693	1.784
	Solar %	0.000	0.000	0.002	0.007	0.063	0.240
	Wind %	0.000	0.000	0.001	0.214	1.580	2.307
	All Combustible Fuels%	65.730	70.755	81.649	78.743	81.177	76.663
Netherlands	Electricity Generated	51924	61970	69427	86029	103376	108946
	Nuclear %	6.090	6.369	4.746	4.297	3.803	3.671
	Hydro %	0.000	0.000	0.122	0.165	0.099	0.090
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.009**	**0.037**	**0.042**
	Wind %	0.000	0.000	0.081	0.964	4.121	4.205
	All Combustible Fuels%	93.910	93.631	95.051	94.278	91.798	91.873
Portugal	Electricity Generated	10409	14726	27284	42215	45579	48718
	Nuclear %	0.000	0.000	0.000	0.000	0.000	0.000
	Hydro %	60.765	53.844	33.492	27.424	16.147	18.273
	Geothermal%	0.000	0.007	0.015	0.190	0.381	0.333
	Solar %	**0.000**	**0.000**	**0.004**	**0.002**	**0.085**	**0.328**
	Wind %	0.000	0.000	0.004	0.396	12.845	15.485
	All Combustible Fuels%	39.235	46.150	66.486	71.989	70.542	65.582
Spain	Electricity Generated	79522	105212	145648	214441	302543	282871
	Nuclear %	9.223	4.664	35.905	27.906	18.669	17.817
	Hydro %	33.682	28.899	17.849	14.669	8.491	10.133
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.004**	**0.008**	**0.845**	**2.135**
	Wind %	0.000	0.000	0.010	2.193	10.660	13.027

	All Combustible Fuels%	57.095	66.437	46.232	55.223	61.240	56.771
United Kingdom	Electricity Generated	253880	266312	300128	360765	373402	359190
	Nuclear %	10.423	12.125	19.546	21.713	12.801	17.473
	Hydro %	1.937	1.913	2.360	2.124	2.473	2.478
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.0003**	**0.005**	**0.006**
	Wind %	0.000	0.000	0.003	0.262	1.906	2.590
	All Combustible Fuels%	87.640	85.962	78.091	75.900	82.815	77.453
Australia	Electricity Generated	71823	92468	144926	195408	240177	241865
	Nuclear %	0.000	0.000	0.000	0.000	0.000	0.000
	Hydro %	20.823	14.756	10.267	8.556	5.020	5.083
	Geothermal%	0.000	0.000	0.000	0.000	0.000	0.000
	Solar %	**0.000**	**0.000**	**0.000**	**0.023**	**0.067**	**0.115**
	Wind %	0.000	0.000	0.000	0.030	1.288	1.574
	All Combustible Fuels%	79.177	85.244	89.733	91.391	93.626	93.228
Japan	Electricity Generated	456723	551778	809939	1019265	1040454	1007606
	Nuclear %	5.176	14.251	23.937	30.282	23.606	26.430
	Hydro %	18.742	16.591	11.742	9.427	7.973	8.098
	Geothermal%	0.000	0.000	0.201	0.304	0.242	0.263
	Solar %	**0.000**	**0.000**	**0.0001**	**0.034**	**0.216**	**0.274**
	Wind %	0.000	0.000	0.000	0.011	0.283	0.293
	All Combustible Fuels%	76.082	69.158	64.120	59.942	67.680	64.642
India	Electricity Generated	NA	NA	275000	NA	785000	899389
	Nuclear %	NA	NA	2.076	NA	1.70	2.07
	Hydro %	NA	NA	24.913	NA	14.60	11.8
	Geothermal%	NA	NA	0.000	NA	0	0
	Solar %	**NA**	**NA**	**0.000**	**NA**	**0**	**0.003**
	Wind %	NA	NA	0.000	NA	1.6	1.99
	All Combustible Fuels%	NA	NA	72.665	NA	82.1	84.04
China	Electricity Generated	NA	NA	650000	NA	3221000	3695928
	Nuclear %	NA	NA	0.000	NA	2	1.89
	Hydro %	NA	NA	19.538	NA	16.2	16.65
	Geothermal%	NA	NA	0.000	NA	0.000	0.004
	Solar %	**NA**	**NA**	**0.000**	**NA**	**0.000**	**0.008**
	Wind %	NA	NA	0.000	NA	0.5	0.72

	All Combustible Fuels%	NA	NA	80.462	NA	81.3	80.7
Brazil	Electricity Generated	NA	NA	NA	NA	NA	466468
	Nuclear %	NA	NA	NA	NA	NA	2.7
	Hydro %	NA	NA	NA	NA	NA	83.8
	Geothermal%	NA	NA	NA	NA	NA	0.00
	Solar %	**NA**	**NA**	**NA**	**NA**	**NA**	**0.000**
	Wind %	NA	NA	NA	NA	NA	0.26
	All Combustible Fuels%	NA	NA	NA	NA	NA	13.13

Source: OECD, World Energy Outlook, 1999; 2000; 2001; 2002; 2003; 2004; 2010, OECD. China; India and Brazil data: IEA, International Energy Statistics, Electricity Generation by Source 2009.

Table 2 Annual Installed Solar Photovoltaic Capacities in Selected Countries and the World, 1998-2009

Year	Germany	Italy	Japan	U.S.	Spain	Others
			---------------- Megawatts ---------------			
c1970						
1998	10	n.a.	69	n.a.	0	76
1999	12	n.a.	72	17	1	95
2000	40	n.a.	112	22	n.a.	94
2001	78	n.a.	135	29	2	90
2002	80	n.a.	185	44	9	121
2003	150	n.a.	223	63	10	148
2004	600	n.a.	272	90	6	84
2005	850	n.a.	290	114	26	41
2006	850	10	287	145	88	223
2007	1,107	70	210	207	560	276
2008	2,002	338	230	342	2,605	766
2009	3,800	730	484	477	69	1,656

Source: Earth Policy Institute, http://www.earth-policy.org/?/data_center/C23/ ,retrieved on April 27, 2012; 1960 data Phech Colatat, Georgeta Vidican, and Richard K. Lester, "Innovation Systems in the Solar Photovoltaic Industry: The Role of Public Research Institutions", Massachussetts Institute of Technology, Working Paper Series, MIT-IPC-09-007, June 2009.

Table 3 U.S. Solar Photovoltaic Production, 1976-1995

Year	Annual Production	Cumulative Production
	Megawatts	
1976	0.3	0.3
1977	0.4	0.7
1978	0.8	1.6
1979	1.2	2.8
1980	2.5	5.3
1981	3.5	8.8
1982	5.2	14.0
1983	8.2	22.2
1984	8.0	30.2
1985	7.7	37.9
1986	7.1	45.0
1987	8.7	53.7
1988	11.1	64.8
1989	14.1	78.9
1990	14.8	93.7
1991	17.1	110.8
1992	18.1	128.9
1993	22.4	151.4
1994	25.6	177.0
1995	34.8	211.8

Source: EPI, http://www.earth-policy.org/?/data_center/C23/, retrieved on April 27, 2012.

Table 4 Annual Solar Photovoltaic Production by Country, 1995-2009

Year	China	Japan	Taiwan	Germany	United States	Others	Total
				Megawatts			
1995	n.a.	16	n.a.	n.a.	35	n.a.	78
1996	n.a.	21	n.a.	n.a.	39	n.a.	89
1997	n.a.	35	n.a.	n.a.	51	n.a.	126
1998	n.a.	49	n.a.	n.a.	54	n.a.	155
1999	n.a.	80	n.a.	n.a.	61	n.a.	201
2000	3	129	n.a.	23	75	48	277
2001	3	171	4	24	100	70	371
2002	10	251	8	55	121	97	542
2003	13	364	17	122	103	131	749
2004	40	602	39	193	139	186	1,199
2005	128	833	88	339	153	241	1,782
2006	342	926	170	469	178	374	2,459
2007	864	938	387	744	269	545	3,746
2008	2,013	1,268	813	1,334	401	1,261	7,089
2009	3,782	1,508	1,439	1,364	587	2,000	10,680

Notes: n.a. = data not available. Rows may not add to totals due to rounding.

Source: EPI, http://www.earth-policy.org/?/data_center/C23/, retrieved on April 27, 20

Table 5: Solar Manufacturer rankings and world market share at benchmark dates: 1988-2011

Year	Company	Country	World production (%)
1988	Siemens Solar	*Germany*	17.5
	Solec/Sanyo	*Japan*	16.5
	Solarex	*U.S.*	10
	ASE (RWE Schott Solar)	*Germany*	8
	Kyocera	*Japan*	5.5
	BP Solar	*U.K.*	4.5
	Photowatt	*France*	2
	Sharp	*Japan*	2
	Helios	*Italy*	1.5
	Top 9 total production as % Total		**67.5**
	WORLD TOTAL PRODUCTION (MW)		**33.9**
2001	Sharp	*Japan*	19.2
	BP Solar	*U.K*	13.9
	Kyocera	*Japan*	13.8
	Shell Solar	*Netherlands/UK*	10.0
	General Electric	*U.S*	6.7
	Schott Solar	*Germany*	5.9
	Sanyo	*Japan*	4.9
	Isofoton	*Spain*	4.6
	Photowatt	*France*	3.6
	Mitsubishi	*Japan*	3.6
	Top 10 total production as % Total		**82.5%**
	WORLD TOTAL PRODUCTION (MW)		**390.5**
2006	Sharp	*Japan*	17.6
	Q-cells	*Germany*	10.3
	Kyocera	*Japan*	7.3
	Suntech	*China*	6.5
	Sanyo	*Japan*	6.3
	Mitsubishi	*Japan*	4.5
	Motech	*Taiwan*	4.5
	Schott Solar	*Germany*	3.9
	BP Solar	*U.K*	3.5
	Shell Solar	*Netherlands/UK*	3.5
	Top 10 total production		**67.9**
	WORLD TOTAL PRODUCTION (MW)		**2,459**
2011	LDK Solar	*China*	10.2
	Sharp	*Japan*	9.5
	Suntech	*China*	8.1
	First Solar	*U.S*	7.8
	JA Solar	*China*	7.5
	Canadian Solar	*China (Canadaregistered)*	6.8
	Trina Solar	*China*	6.4
	Yingli Solar	*China*	5.8
	Hanwha Solar	*China*	5.1
	Jinto Solar	*China*	5.1
	Top 10 total production		**72.2**
	WORLD TOTAL PRODUCTION (MW)		**29,500**

Sources:

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